6-11-2014

Benchtop centrifuge for materials science

Jose Lizheno
Santa Clara University

Nathaniel Tseng
Santa Clara University

Ryan Tsuzaki
Santa Clara University

Santa Clara University

DEPARTMENT of MECHANICAL ENGINEERING

Date: June 11, 2014

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Jose Lizheno, Nathaniel Tseng, Ryan Tsuzaki

ENTITLED

Benchtop Centrifuge for Materials Science

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

Robert A. Marley

THESIS ADVISOR

DEPARTMENT CHAIR

Centrifuge for Materials Processing Labs

by

Jose Lizheno, Nathaniel Tseng, Ryan Tsuzaki

SENIOR DESIGN PROJECT REPORT

Submitted in partial fulfillment of the requirements
for the degree of
Bachelor of Science in Mechanical Engineering
School of Engineering
Santa Clara University

Santa Clara, California

June 11, 2014

Abstract

The Benchtop Centrifuge for Materials Science was designed to be a versatile, cost-effective, user-friendly and safe centrifuge for the university setting. While a prototype was not completed due to running out of time for assembly, various forms of analysis were conducted including Natural Frequency Analysis and Finite Element Analysis. The team hopes that the work completed will provide a useful starting point for other teams that may wish to continue the project in the future.

Table of Contents

Figures

Chapter 1 - Introduction

From manufacture and medicine to agriculture and mining, there are many fields that benefit from the ability to efficiently separate solutions. The separation of solutions is often achieved through some combination of precipitation, filtration and sedimentation. Precipitation is the process by which chemical reaction(s) select the desired compound by changing its phase from liquid to solid. Filtration is the process by which particles of a desired size are selected either to discard or keep. Sedimentation is the process by which the application of force on particles causes particles of varying densities and sizes to settle at different rates. A device that expedites the sedimentation process by rotating a sample is called a centrifuge.

Figure 1: Centrifuge Operation

Producing high quality compounds is not possible without the correct types of machinery. Separating solutions is very important in attaining a high quality material, and as such, centrifuges are in great need. However, smaller materials labs do not always have access to centrifuges and often have to purchase their compounds from larger labs, increasing the cost of such projects and generating overhead time for shipping and handling.

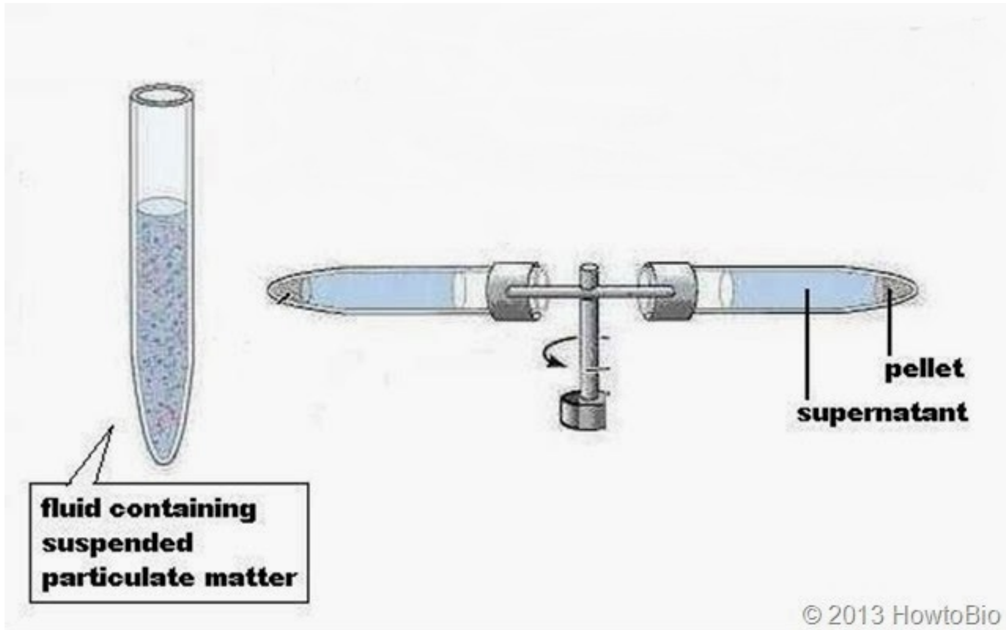


Figure 2: Solution Separation

By improving the efficiency of the refining process in a way that is more accessible to smaller labs, research will be enabled at smaller institutions with lower budgets.

1.1 Review of Literature

Just as there are many applications in which centrifuges are used, there are also many differences in design to tailor the centrifuge for each of those applications. Centrifuges can be divided into two major categories: stationary devices and rotating devices.[1] A stationary centrifuge sprays the solution into a cylindrical or conical shaped container. The denser substances will travel to the outside of the container while the lighter substances remain closer to the center of the cylinder. One notable design for stationary centrifuges is the Screen Scroll Centrifuge (see **Figure 3**).

[1] Ed. K. Lee Lerner and Brenda Wilmoth Lerner,"Centrifuges".

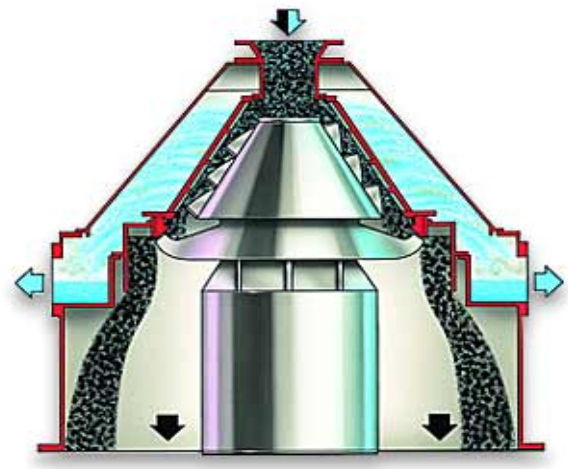


Figure 3: Screen Scroll Centrifuge

This type of centrifuge uses centrifugal force to feed the slurry into a screen to separate the solution. It is commonly used in the coal processing industry to dewater tiny particles.[2]

In a rotating centrifuge (see **Figure 4**), the solution is placed in containers which are then spun rapidly. As the centrifugal acceleration applies force on the fluid, the denser or larger particles will settle to the bottom of the containers. Following this process the containers usually undergo a decanting process and either the particulate or the fluid is kept depending on the application.

[2] S. Rangarajan, “Centrifuge Technology”.

Figure 4: Magnetic Centrifuge

In 2013, Mechanical Engineers from South Korea used magnetic bearings to create a rotating centrifuge without a vacuum chamber.[3] The team remarked that a vacuum, vacuum pump, diffusion pump, and vacuum chambers occupy about 50% of the volume in centrifuge systems, making the system bulky and complicated. Moreover, a vacuum chamber requires complicated methods to create a seal between the vacuum and non-vacuum components. Therefore, by eliminating the vacuum chamber from the centrifuge, the device is made simpler and thinner.

[3] Cheol Hoon Park, Soohyun Kim, and Kyung-Soo Ki, "Review of Scientific Instruments 84, 095106”.

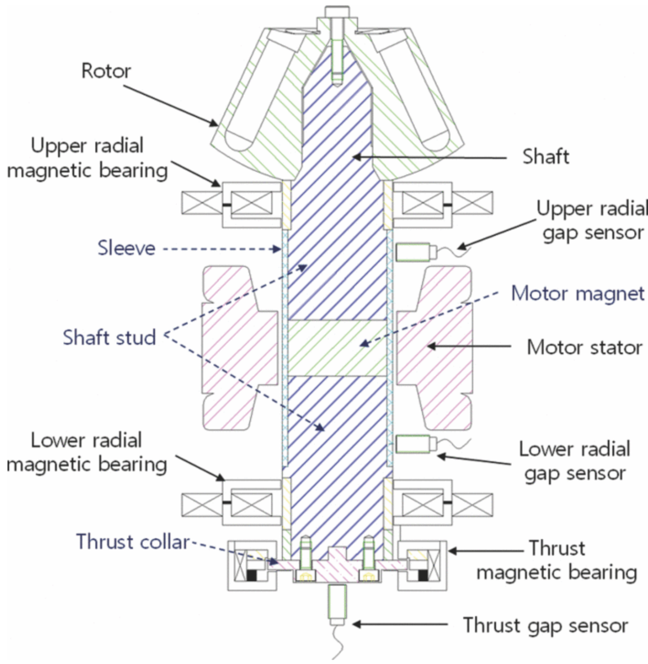


Figure 5: Vacuum chamber-free centrifuge

Magnetic bearings also hold other advantages as well. By applying magnetic bearings to the centrifuges, the spindle diameter can be increased, allowing a higher torque to be transmitted from the motor to the rotor. This torque can be increased in order to overcomes the windage losses experienced by vacuum chamber centrifuges. Magnetic bearing centrifuges can also be controlled while in motion, which allows for much quicker and effective response to an unbalanced response. These advantages have been found invaluable in separating extremely small particles and sensitive substance, such as in the processing of milk, beer, wine, vegetable oils and other food products.

Rotating centrifuges are also subcategorized into industrial centrifuges and ultracentrifuges. Industrial centrifuges range in size from 4 inches to 4 feet in diameter, and their rotational speed can range from 1,000 to 15,000 revolutions per minute. Ultracentrifuges (see **Figure 6**) on the other hand, can only hold containers 0.2 inches in diameter or less; however, they can achieve a rotational speed of 230,000 revolutions per minute.

Figure 6: Ultracentrifuge

Heraeus was one of the first companies to create a table-top centrifuge with a floor-standing unit.[4] The table top centrifuge, known as Biofuge Stratos, was built in 1997 with the capability of reaching $45000 * g$ in 25 seconds. It also has a safety feature to detect any imbalance in the system and immediately stop the process. Since then, table-top centrifuges have become popular due to their capability and compactness of size.

Centrifuges even have applications in deepwater drilling systems where a duel gradient based on the dilution of riser mud requires economically separating the riser mud into a low-density dilution fluid and a higher density drilling fluid. A study to investigate the separation method on both hydrocyclones and centrifuges compared the efficiency of each method.[5] The laboratory centrifuge was able to separate the riser mud into near ideal densities for dilution and drilling fluid. However, the dense slurry retained in the centrifuge had lower electrical stability than the feed stream. The hydrocyclones achieved much less contrast in density between the low and high density discharges, but their use

[4] Current Opinion in Neurobiology, 1997, Vol.7(5), pp. iii-iii) Peer-Reviewed Journal.
[5] John Shelton, John Rogers Smith, Anuj Gupta, "Experimental Evaluation of Separation Methods for a Riser Dilution".

consistently resulted in a beneficial increase in the stability of the mud emulsion in all of the flow streams and gave more desirable rheological properties.

1.2 Problem statement

The goal of the Benchtop Centrifuge for Materials Science Team is to advance the capabilities of small materials science labs by creating a centrifuge that is versatile, cost-effective, user-friendly, and safe. These qualities were identified as important to the university research setting (see Section 2.1). A compact size and high maximum speed will grant the centrifuge the versatility it needs to accommodate the various experiments research may ask of it. A long life-time and competitive cost will help it to stand out among existing centrifuges as cost-effective. User-friendliness will be achieved with accessible controls and straight-forward lab procedure. Finally, the implementation of an emergency response system and design integration will protect the user and product in the case of unsafe conditions.

Chapter 2 - Systems-Level Overview

A centrifuge is a device that separates solutions by using centripetal acceleration to hasten settling *via* the sedimentation principle. In other words, by spinning a sample solution, the larger and denser particles in the suspension tend to "fall" to the bottom, thus separating the substances. A relatively simple device, the centrifuge's system (see below) is quite straight forward.

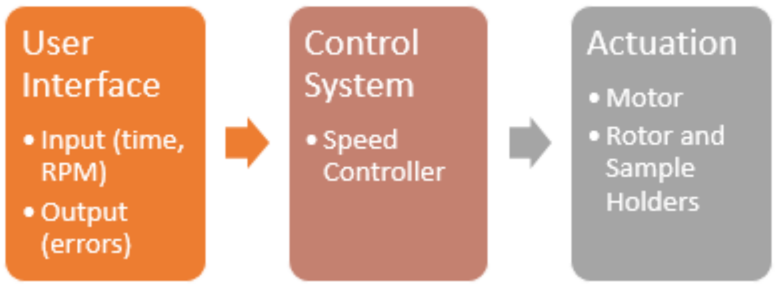


Figure 7: Centrifuge System Overview

Use starts at the user interface. In the case of this centrifuge, the user interface is the control module where the user inputs his or her run parameters. The parameters accepted by the centrifuge include run time and run speed. Run speed can be entered as either the revolutions per minute (RPM) or the relative centrifugal force (RCF). The user interface also notifies the user of completed runs or runs halted due to errors.

Once the user inputs the run parameters, the centrifuge's control system then interprets the parameters into instructions for the motor. This occurs in the speed controller, after which the instructions are sent to the actuators to begin the run.

Actuation occurs primarily in the rotor and surrounding parts, such as the motor and sample holders. At this point the rotor spins the samples, applying the acceleration indicated by the input parameters.

2.1 Customer Needs and System Specifications

Customer needs research was composed of surveying two university faculty members (the primary users of the centrifuge), reviewing relevant materials science experimental procedure, and comparing the features of existing products. This research indicated that customers valued versatility, user-friendliness, cost-effectiveness, and safety. Deconstructing these subjective values provided concrete specifications for the design.

As a tool primarily seeing use in a research setting and for lab demonstrations, the centrifuge needs to be usable in a wide variety of experiments. A survey of common fabrication processes indicated that a maximum relative centrifugal force of $5000 * g$ would accommodate a large majority of experiments. Additionally, since the centrifuge will be used at the university, it is more likely that the centrifuge will see quick successions of traffic compared to one used in industry. Accommodating these periods of high traffic meant that the clean-up procedure needed to be kept short and simple. Further, the centrifuge's use in lab makes it desirable that the centrifuge fit atop a lab bench. Thus, we decided that an optimal centrifuge size would be approximately 2 square feet as it would fit on a lab bench while still being large enough to hold numerous samples..

Because the Benchtop Centrifuge for Materials Science will not be entering a pioneer market, it will need to take into account and address its competition. While it may not be within the scope of this project to develop the most cutting edge product with the newest and best features, it is still important to recognize that a product can still be cost-effective if it provides more services than its competition at its specific price. We determined that it would be possible to create a centrifuge that offered competitive quality at the price of $1500. Most close comparisons on the market are offered at about $3000-5000, as seen in our benchmarking research in **Appendix A1**.

User-friendliness was also a highly desirable quality due to the fact that a number of the users for this product would not be extensively trained prior to use. Translating this into design specifications resulted in the focus on designing user input and error messaging to be as clear as possible. One feature that embodies this concept is the centrifuge's ability to receive input both in RPM and in RFC.

The centrifuge accelerates solutions at speeds up to 4000 RPM. Due to the high accelerations the centrifuge can reach, the device is very dangerous by nature since the operator might be seriously injured if he/she came in contact with any of the fast moving parts. In order to prevent this from happening, a frame was designed in order to cover the moving part. The frame will help to ensure that the operator will be protected even when the device is moving at high speeds. Another serious safety concern is that at high speeds, the centrifuge could become unbalanced or something could get stuck in the rotor. In theory, this would cause the accelerating parts to move in a manner that the centrifuge is not designed to operate at and cause it to react violently, potentially seriously harming the operator or people nearby. In order to limit this safety hazard, we designed an emergency system. During use, this system will be constantly determining if the centrifuge is accelerating properly and if it is balanced. If these conditions are not met at any point in time, the emergency system will override any current controls, shut the unit down, and stop the rotation of the centrifuge's rotor as quickly as possible.

Designing a safe device is especially important because the device may be used in lab demonstrations by untrained students. Multiple types of analysis, including vibration analysis, natural frequency analysis and strain analysis, were conducted to meet the safety requirements without sacrificing the functionality of the centrifuge's design. Finally, testing and verification of part integrity were planned to ensure that the product was performing to specification. Problems that arise will be addressed to ensure the finished product will keep the user safe. If we are not able to ensure the centrifuge is not able to meet the specifications within our safety goals, we are ethically bound to not release our product to the public. An unsafe product could injure its user, and if this were to happen, we would be held responsible for unsound and unethical design.

2.2 Functional Analysis

The function of the centrifuge is to spin the sample holders at the speed required by the user and keep the user safe.

2.2.1 Functional Decomposition

Spinning the sample holders at the required speed involves several functions. In addition to having the mechanical power to spin at the required speed, the centrifuge also has to determine what voltage is associated with that speed and maintain that speed for the duration. This requires control analysis to provide proper feedback and reject disturbances.

The centrifuge is also intended to keep the user safe. This is handled mostly by the frame by reducing user access to parts while they are in motion, and also by the control system which will detect and halt the centrifuge in the event of an emergency situation.

2.2.2 System Layout

The centrifuge was divided into three subsystems: the frame, the rotor and the control system. Each subsystem is interconnected and affects the function of the other subsystems. The frame supports and provides stability to the parts of the rotor and the control system. In turn the control system determines the output for the rotor and detects changes in position *via* the frame. The rotor actuates the instructions of the control system and is supported by the frame.

2.2.3 Inputs and Outputs

The inputs of the centrifuge are the run speed and run time parameters provided by the user. This is to be converted to the output of rotation of the rotor, or error messages if that is interrupted or impossible. These inputs will be constrained by the safety thresholds on the centrifuge, preventing the centrifuge from spinning too fast or in a dangerous fashion.

2.3 Benchmarking Results

Benchmarking is the process of comparing the specification of already existing products in order to determine reasonable goals for an upcoming project. In the development of the Benchtop Centrifuge for Materials Science, most of the existing references used for benchmarking were other centrifuges (see **Appendix A1**). The products compared were the QBC® Horizon 755VES Centrifuge, the Heraeus™ Labofuge™ 400 Centrifuge and the Horizon Centrifuge Model 853VES.

The results of the benchmarking process were highly informative. By researching three existing centrifuges, we were able to determine the specifications of devices that people currently use. This helped us to determine and set specific goals for our centrifuge design. While our benchmarking research including numerous qualities such as the lifetime of the product, relative centrifugal force, timer capabilities and more, the most valuable information gained was the prices and maximum speed of the centrifuges. From our research we were able to determine that centrifuges currently on the market reach speeds of around 4,000 RPM, while higher end models even reach 11,000. Additionally, we found that these centrifuges cost around $3000. Therefore, in order to strive to compete with the existing models, we decided we wanted our centrifuge to reach a speed of 4,000 RPM and limit our budget to under $3000.

2.4 System Level Issues

As with any design, the design of the Benchtop Centrifuge for Materials Science required that particular options be selected. In this case, preliminary selections included different rotor options and solution handling options. These decisions affect not only the efficiency of the product, but the features and services the product is best at providing. As such, a well conducted study of customer needs will inform these decisions.

2.4.1 System Options

In order to ensure that the centrifuge best met the needs of its target, discussion was held to make the design decisions by selecting from multiple system options. Since the centrifuge will be used for research purposes, there were many optional features that could have been included in its design. Some of features included automatic counter-balancing features, benchtop fastening features, and heating and magnetism features, and built-in filters. Most of these were deemed outside of the scope of this project, offering too little convenience for the amount of time they would require to develop.However, some design decisions were given more consideration, namely the solution handling options and the rotor options.

2.4.1.1 Solution Handling Options

The solution handling design often has the great effect on the performance of the centrifuge as well as the lab procedure for that centrifuge. The two options considered for the Benchtop Centrifuge for Materials Science were continuous flow and sample batches.

Continuous flow designs employ a continuous flow of solution, which is separated over the course of its flow through the centrifuge. In this configuration the centrifuge can be combined with a decanter, a device that removes the fluid from the solution once the solids have been separated out. Continuous flow centrifuges boast high efficiencies and fast rates of solution separation and also tend to have simpler lab procedures due to this fact. The Flottweg Decanter Centrifuge, shown in **Figure 8** is an example of a continuous flow design. Using this method, the solution containing both liquid and solid particles will continuously be flowed into the decanter through the feed inlet. As the fins inside the sedicanter rotate to guide the solid discharge in leaving the system, the liquid particles would be able to be collected inside the chamber.

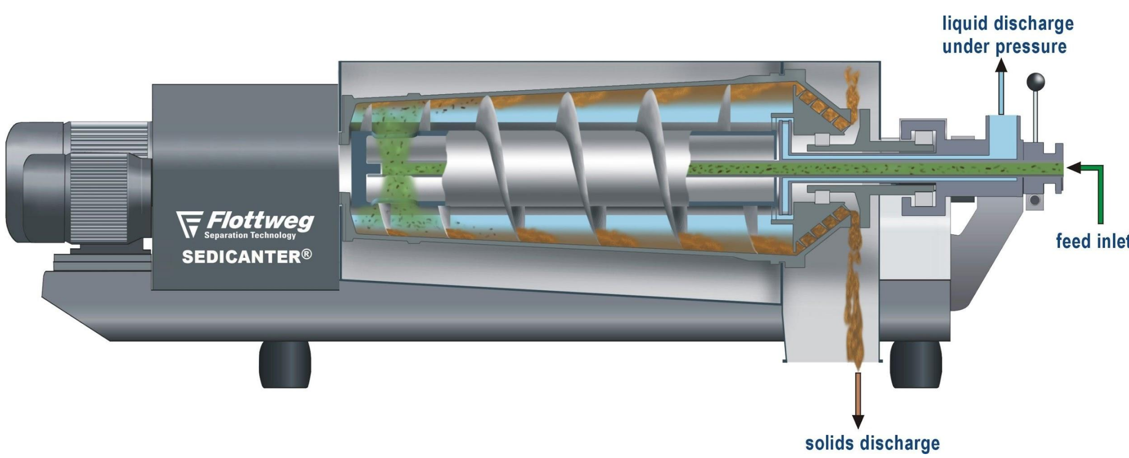


Figure 8: The Flottweg Decanter Centrifuge

One drawback of a continuous flow centrifuge is that the solid particulate is all handled the same way—separated from the fluid. This may be a significant disadvantage in a process intended to isolate particulate of a specific quality or size. Additionally, continuous flow designs are difficult to stop for discrete or chemically different samples once started. This would make the testing of a number of smaller volume samples more difficult.

Separating samples into batches is another common design option. These batches are then put into test tubes which spun while held by the sample holder (see **Figure 9**). Because each sample is in a separate batch, greater control is given to the lab technician in terms of the speed of each run and the specifics of each sample.

Figure 9: Separate sample centrifuge

However, the lab procedure for their use tends to be more complicated. Each sample holder must be filled individually and the user must ensure that the imbalance is not introduced into the centrifuge by filling the samples unevenly. Further, separate sample centrifuges rarely have automated decanter features.

2.4.1.2 Rotor Options

Two options were considered for the rotor: a fixed angle rotor or a swinging bucket rotor. It was important to select the right option for our market of university students and researchers. Fixed angle rotors are dome shaped and the test tube hole containers are directly on the rotor. These holes will put the test tubes at an angle less than 90°. Swinging bucket rotors have rotating arms around the center of the rotor that carry test tubes. These test tubes are placed vertically and do not have any tilt like the fixed angle rotor sample placement.

A fixed angle rotor tends to have a longer lifetime and is easier to model because they have fewer moving parts. However they also tend to be less efficient than a swinging arm rotor because the angle of the rotor arms splits the centrifugal acceleration, some of which is not used. Contrastingly, a swinging bucket rotor will tend to have a shorter lifetime and more complex modeling and fabrication because it has moving parts. However, because the arms of the rotor swing up to match the direction of acceleration while running, the transfer of kinetic energy is more efficient.

2.4.2 Design Choice Rationale

The Benchtop Centrifuge for Materials Science is initially intended for use in the Santa Clara University Materials Science Laboratory which may use various solutions in the same run. It would be inefficient to use a continuous flow design that prepares samples in bulk. It is important that neither the sediment nor the solution be automatically discarded because depending on the refinement process, either of them may be the target reagent. Further, it was noted that one trade-off of automation is often the loss of this type of versatility. For example, attempting to increase production by having a continuous flow of fluid within the centrifuge would be un-ideal because sample sizes used in research rarely use volumes large enough to justify such a feature and having the automatic feature would make starting and stopping the sedimentation process more cumbersome. Based on this consideration, a more individualized separate sample method was chosen over continuous flow.

In choosing the rotor design, design for versatility was crucial. The increased efficiency afforded by the swinging arm rotor design far out-weighed the simplicity of a fixed angle rotor because it would enable more materials refinement processes, and thus more types of research, to be conducted.

2.5 Project Management

As with all large projects, management was required to ensure success. It was particularly important to anticipate potential challenges or risks that may have been encountered so that preventative measures or solutions could be implemented. Additionally, substantial management was required in order to set plans and goals for various aspects of the design process, such as the budget, timeline, and team dynamics.

2.5.1 Project Challenges and Team Constraints

The Benchtop Centrifuge for Materials Science was a fairly straight forward project. The main challenge presented itself in the form of an increased focus on producing a working concept rather than just a proof of concept.

Throughout the time working on the project the team encountered two main types of problems: motivation and bottlenecking. Motivation ended up being an issue when team members did not strive to produce quality work outside the requirements of coursework. Poor planning lead to multiple instances of bottlenecking where project progress was halted in one area until sufficient progress in another area was completed. This was especially prevalent in the inability to assemble the centrifuge while parts were being shipped.

2.5.2 Budget and Timeline

The main issues regarding the budget of the project were determining cost estimations of the parts (see **Appendix B2**). While acquisition of funding is always a concern, initial research indicated that commercial centrifuges were more expensive than expected. This indicates that some part of the project is underestimating the required cost for that subsystem. Additional research and discussion with experts will help to expose these areas.

A timeline was created to enumerate the tasks to be completed and schedule the order of their completion (see **Appendix B1**). The primary goal of this timeline was to provide ample time for testing and iteration. Proper testing and verification is an important step in the development of any product, and our team was careful not to underestimate the amount of time this would require. Therefore, in order to properly adjust for this, assemblage and design deadlines were pushed up earlier.

2.5.4 Design Process and Team Management

The design process of this project relied heavily on research of existing centrifuges. In addition to looking at specifications of similar products, our team has also conducted research by surveying experts and nearby centrifuge users about appropriate benchmarks for our project.

Team management has assumed team member autonomy. The team met periodically throughout the week in the late morning to discuss direction and work on objectives. While work was accomplished during the regular meetings, larger objectives were often split into sub-objectives and each member made responsible for a portion of the objective. These sub-objectives were to be completed before the next meeting so that feedback and revision can occur during the meetings. If additional work time is required an agreeable time is decided upon (generally in the evenings after most activities) at that point. Our team also met our faculty advisor to check in and ask questions about direction during the Friday meeting. This has been especially productive because our advisor also happens to be our client.

2.5.5 Risks and Mitigations

Most of the risks associated with this project involved not meeting specified requirements for the product. For example, if the centrifuge failed to meet requirements for safety or productivity, it would not be usable in the lab as intended. Further, there was a risk that underestimation of budget could lead to the incompletion of the project. All of these risks were mitigated by ensuring realistic design specifications and a steady working pace for the development of the project.

Chapter 3 - Subsystems

The centrifuge's function is divided into three subsystems: the frame, the rotor, and the control system. The frame includes the supporting structure in which the rotor and control system subsystem are housed, and its primary functions are to protect the user when the centrifuge is running and provide stability. The rotor subsystem is responsible for transferring the torque created by the motor to the samples. Finally, the control system is responsible for receiving input from the user, interpreting the desired conditions into motor instructions, providing the user with feedback, and detecting dangerous conditions in which the centrifuge would need to be stopped.

3.1 Frame

The frame of the centrifuge is important because it houses the rotor, samples, and control system. It is important that the frame be extremely sturdy so it will be dependable even when the centrifuge is being operated at high speeds. Additionally, the frame must also be able to withstand impact as it is the only barrier between the user and the moving parts of the rotor. Should any malfunctions occur, the frame will need to be able to block any parts from harming the user. Thus, a strong material must be used for the frame, and it must be thick enough in order to provide the stability needed. We decided that the frame of the centrifuge fit within a footprint of 69 cm by 61 cm and be no taller than 31 cm since we wanted to limit the amount of space on the lab bench, while still having the frame large enough to allow the rotor to spin with its buckets fully extended.

In addition to providing strength and stability, the frame also isolates the control system from the samples. The samples that the centrifuge will process could damage the unit if they were to come in contact with the control system. As such, the frame is responsible for keeping the two from contacting each other as a wall between the two.

All centrifuges currently on the market that we researched followed a similar design for the body. The centrifuges that we researched all have an inner centrifugation chamber that is made of 304 stainless steel. Additionally, these centrifuges feature a body around the centrifugation chamber made of galvanized steel. Lastly, these centrifuges all have a plastic outer layer that covers the steel.

Prior to research, we had planned to create our frame out of aluminum as it is a material that we commonly see used in manufacturing equipment. However, upon further inspection, steel was a better choice due to its greater modulus of elasticity of $3 * 10^7 psi$, as compared to that of aluminum which is around 10^7 psi. This greater stiffness will be advantageous as we want the frame to be as stiff as possible in order to minimize any deforming when the centrifuge is in use. While steel is heavier than aluminum, this could be seen as advantageous. Although the added weight will make the centrifuge more difficult to transport, it will help to make the centrifuge more stable. The frame assembly can be seen below in **Figure 10**.

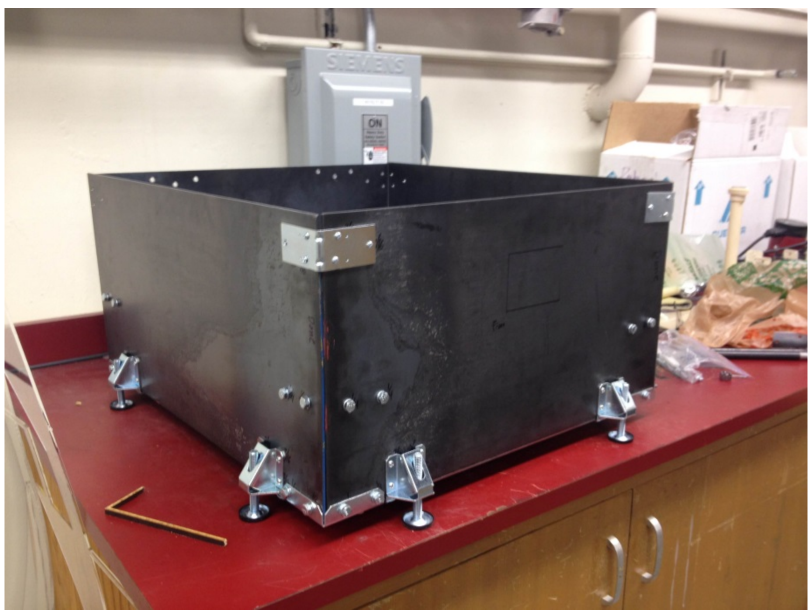


Figure 10: Centrifuge Frame Assembly

In order to add support to the rotor, the frame also houses a bearing (see **Figure 11**). Mounted on another plate of steel above the motor, the bearing will fit around the spindle. This added support will help minimize the effects of any tilts or vibrations that the spindle and rotor may experience during operation. Additionally, since the steel plate securing the bearing will be situated above the motor, this bearing and steel plate will help to prevent anyone from accidentally disturbing the wiring of the control system, and will also prevent samples from falling into the control system.

Figure 11: Bearing Attached to the Middle Plate

3.1.1 Frame Analysis

One of the primary concerns in the design of the centrifuge is the user's safety. Since the frame is the barrier between the user and the potential dangers of the spinning rotor, it was crucial that substantial analysis was conducted on the frame to ensure it would be reliable in operation. Shear loading analysis was conducted to ensure the bolts of the frame would be able to support the loads of the centrifuge. An impact force analysis was done to determine if the frame would be able to contain any projectiles that may impact it in the event of a mishap. Lastly, a natural frequency analysis was conducted to determine the maximum allowable speed the centrifuge could operate at while still avoiding resonance.

3.1.1.1 Shear Loading on Joints

Because the frame is constructed out of steel, the five steel faces of the 1/8 in frame are quite heavy. At around 8 lb per square foot, the entire frame weighs approximately 100 lb. Thus, analysis on the shear stress of the bolts was conducted to ensure that the fasteners were capable of supporting the considerable weight of the frame over the lifetime of the centrifuge. In this case, the bolts are undergoing a single shear as they are fastening a face of the frame to one of the corner brackets. In order to conduct this analysis, we first researched the yield strength of the bolts that we are using and found it to be 57,000 psi. We then divided this number by a factor of safety of 2. By comparing this quotient to the variable load value divided by the cross sectional area of the bolt (0.049 in), we were able to find the maximum acceptable load that the bolts are able to support. It is important to note that since each face has 12 bolts that share the load of the steel plate, the value for load was multiplied by 12. We therefore concluded that the bolts for each face could support a load of 11,172 lb, which was well above the weight of the entire centrifuge unit. A more in depth look at the calculations can be found in **Appendix C1**.

3.1.1.2 Impact Force on Walls

We also conducted an important analysis on the impact force on the frame walls in order to ensure that the centrifuge operator will be safe in the event that a part comes loose during the centrifuge's operation. Since the centrifuge will be spinning at such high speeds, it is crucial that we can verify that the frame will be able to withstand any forces that it might experience if a part were to impact it during operation. In order to verify this, we considered the worst case scenario of a bucket coming loose while the centrifuge is spinning at its maximum speed. Firstly, using a rotor diameter of 0.3905 m and the maximum rpm of 4000 RPM, we converted the angular velocity of the centrifuge to its linear velocity to find that it was $v = \frac{\pi * d * RPM}{60} = 81.786 \text{ m/s}$. Using this linear velocity and the buckets mass of 0.5 kg, we determined the dynamic energy of this bucket using the kinetic energy equation. When the bucket impacts the frame wall, the kinetic energy of the bucket is converted to work. Thus, by using the equation for the work expressed as a function of the distance to slow the bucket's movement we were able to determine the impact force of the bucket. Assuming a slow down distance of 0.5 in, this resulted in an impact force calculated to be $F = \frac{m * v^2}{s} = 2.9601.1$ lb. This impact force was then divided by the number of bolts per frame face in order to find the force experienced by each bolt. This number was then compared to the tensile strength of the bolt multiplied by the cross sectional area of the bolt and divided by a factor of safety in order to determine if the bolts would be able to withstand the impact of the bucket. The impact force of the bolt divided by 12 was found to be 2466 lb, while the allowable load with a factor of safety of 2 was calculated to be 2940 lb. Thus, it is clear that the actual load is less than the maximum allowable load and therefore the frame will be able to withstand the any forces it may experience in the event of an accidental impact. A more in depth look at the calculations can be found in **Appendix C2**.

3.1.1.3 Natural Frequency Analysis

Another concern regarding the frame of the centrifuge is its natural frequency. Like all bodies, the frame of the centrifuge has a natural frequency specific to its geometry and properties. The natural vibration of the frame is different than forced vibrations which occur at the frequency of an applied force. In the case of the centrifuge, the device does experience forced vibrations caused by the motor and spinning rotor. If a forced frequency is equal to the natural frequency of a body, then the amplitude of vibration will significantly increase. This circumstance is known as resonance and should be avoided in order to minimize the vibrations of the frame. If the frequency of the motor equals the natural frequency of the frame then resonance will occur and the centrifuge will experience much greater vibrations that could affect the functionality and safety of the device. Therefore, in order to ensure the natural frequency does not overlap with the frequency of the rotor, the natural frequency of the frame needed to be determined so that we would know the limit for the speed that we could safely operate the centrifuge. Initially, we attempted to determine the natural frequency of the centrifuge by calculating it by hand. However, this proved to be far too challenging as the geometry of the frame is relatively complex in regards to calculating natural frequency. Therefore, we decided to utilize Ansys to determine the natural frequency of the frame.

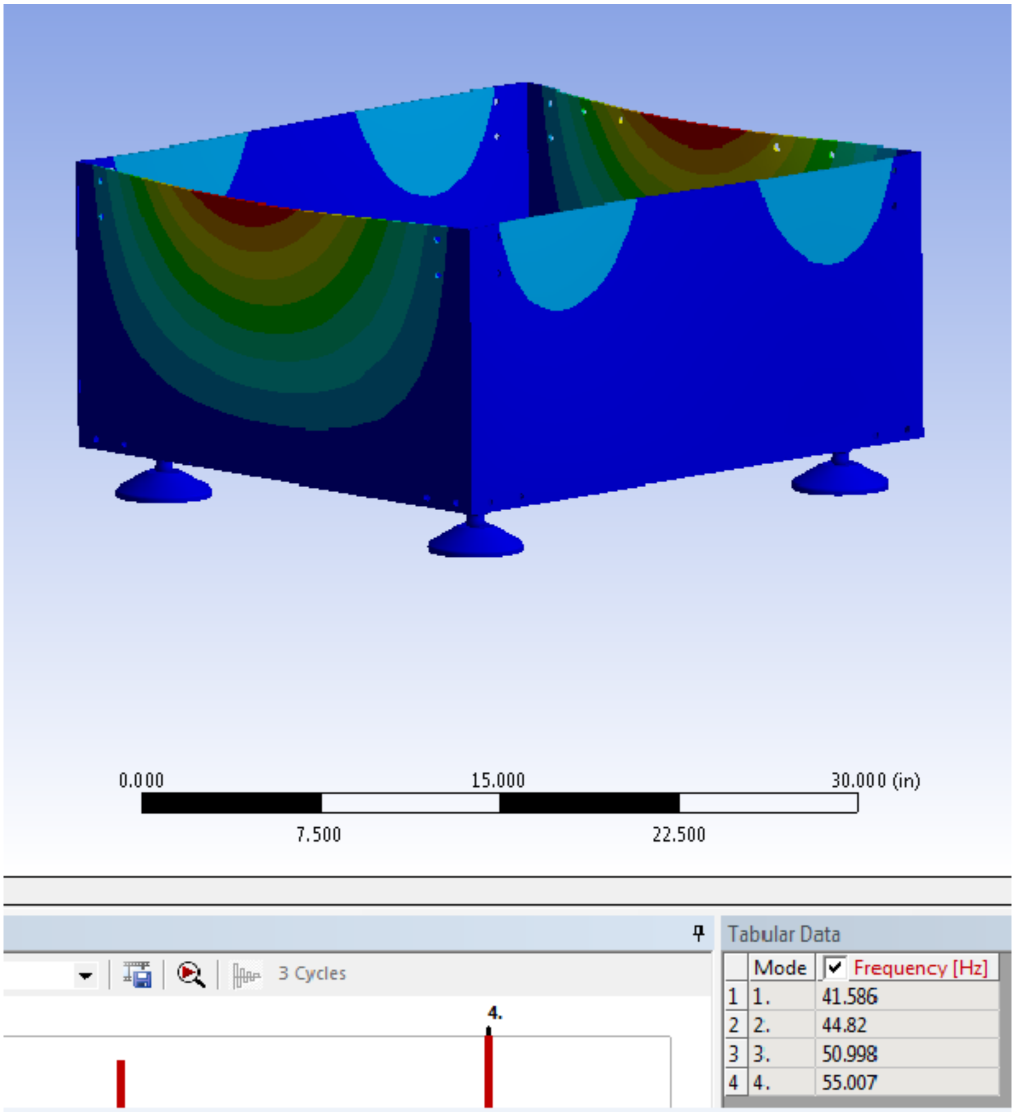


Figure 12: Natural Frequency Analysis of the Frame Using Ansys

After modeling the frame in Ansys, setting the appropriate material properties and fixed supports, and generating a mesh for the system, we were able to find that the fundamental frequency of the centrifuge was 41.586 Hz. Similarly, the second, third, and fourth mode frequencies were 44.820, 50.998, 55.007 Hz respectively. Based off this result, it was determined that the centrifuge should not be operated at a speed greater than 41.586 Hz or 2,495 revolutions per minute in order to ensure that the system does not experience resonance.

3.2 Rotor

The rotor subsystem is responsible for transferring the torque from the motor to the samples. The main challenge in the selection of the rotor is the need to accommodate the desired acceleration and speed while ensuring user safety and product lifetime while maintaining a low cost for the whole product. To meet the needs of the laboratories that the centrifuge is intended for, the rotor should be able to reach a speed of around $4000\ RPM$ or create an RCF of up to $3500 * g$. The rotor subsystem itself is composed of the motor, rotor spindle, rotor (part), and the sample holders.

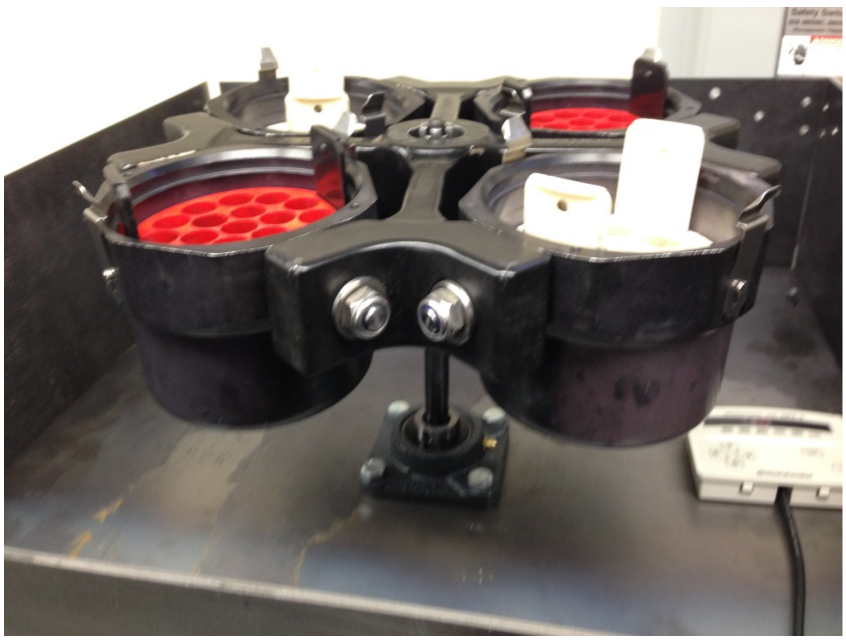


Figure 13: The Rotor Sub-System

3.2.1 Motor

The motor provides the torque required to spin the rotor and centrifuge samples. Being the only component that supplies torque to the rotor, the motor should be able to provide a sufficient amount of torque (see **Appendix C3**). A brushless DC motor with $0.4\ N \cdot m$ rated torque was found to be adequate in supplying the rotor enough torque to reach its maximum speed of $4000\ RPM$ in less than 18 seconds.

Figure 14: BLE23AR30F Brushless DC Motor

BLE23AR30F Brushless DC motor is a product of Oriental Motor Corporation. The motor is versatile in handling various types of work. One of its particular uses is to provide rotational movement which is facilitated by connection of the motor shaft. The connecting shaft will be locked together with the motor using a keyway mechanism. This device will be able to carry a mass of up to 20.4 kg while maintaining its speed up to 4000 RPM.

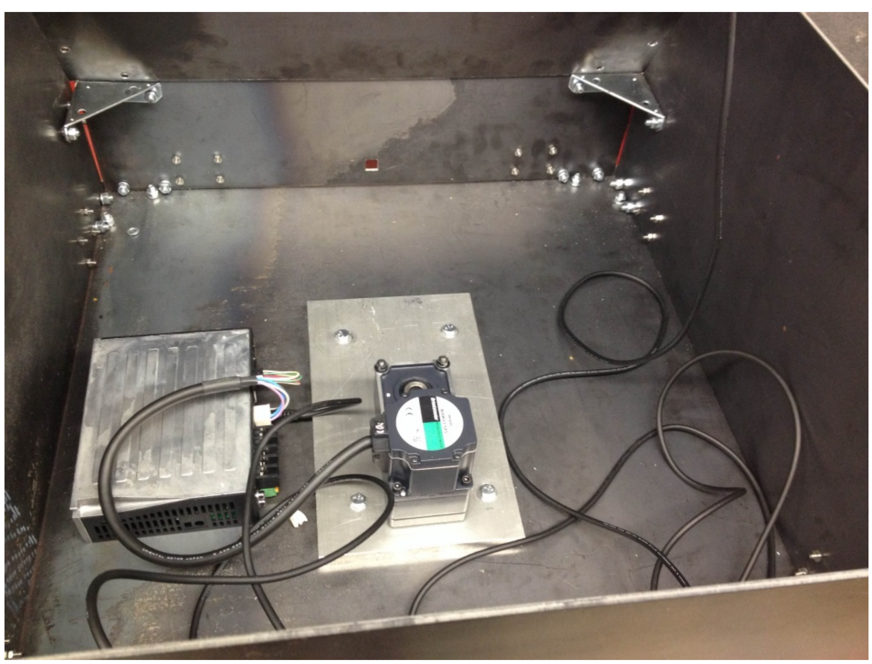


Figure 15: Motor Connected to Frame with Mount

3.2.2 Rotor Spindle

The rotor spindle functions as the connecting part between the motor and the rotor (shown in **Figure 16**). While selecting a material for the spindle, the following factors were considered: the spindle must withstand the torsion applied by the motor, carry a 7.3 kg rotor, and not be excessively heavy. It was also necessary that the material be safe to modify with the equipment available to us at the Santa Clara University Fabrication Lab. The material 1045 Cold Rolled Steel stood out as a good fit for these criteria with relatively high tensile yield strength of $450\ MPa$ and the ability to be modified in the lab.

Figure 16: Rotor Shaft

After selecting a material, Finite Element Analysis was conducted in order to ensure that the spindle was capable of handling the stresses it would undergo when in use (see **Appendix C**). Simplified drawings of the rotor parts were created, and a torque corresponding to $4000\ RPM$ was applied to the spindle in order to analyze the stresses on the spindle. The results of the Stress Analysis (see **Figure 17**) showed that the spindle experienced between $2{,}162.9\ \mathrm{N/m^2}$ and $76{,}122.4\ \mathrm{N/m^2}$.

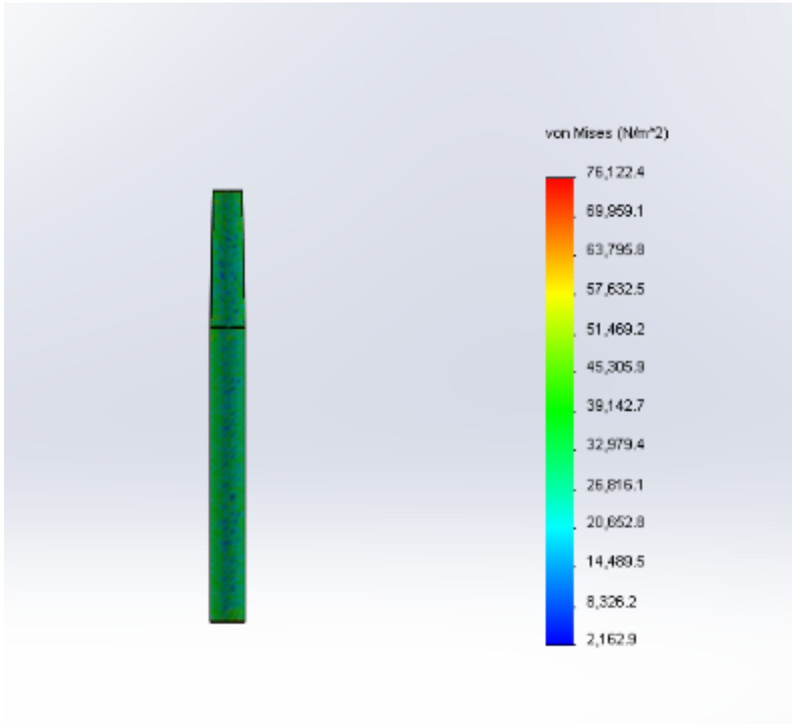


Figure 17: Finite Element Stress Analysis

However, these extrema were not the general loading on the spindle. Most of the spindle experienced loads around $40{,}000\ \mathrm{N/m^2}$ with intermittent local areas of decreased loading. The highest range of the loading was only found to be experienced at the very bottom of the part, where edge conditions will differ from the design anyway. These stress values were then compared to the plastic yield strength of Steel Alloy (the preset that best matched 1045 Cold Rolled Steel, our spindle's material) to provide meaningful insight in Factor of Safety Analysis. The results of our Factor of Safety Analysis (see **Figure 18**) showed that throughout the part, the factor of safety varied between 724.47 and 25,497.88.

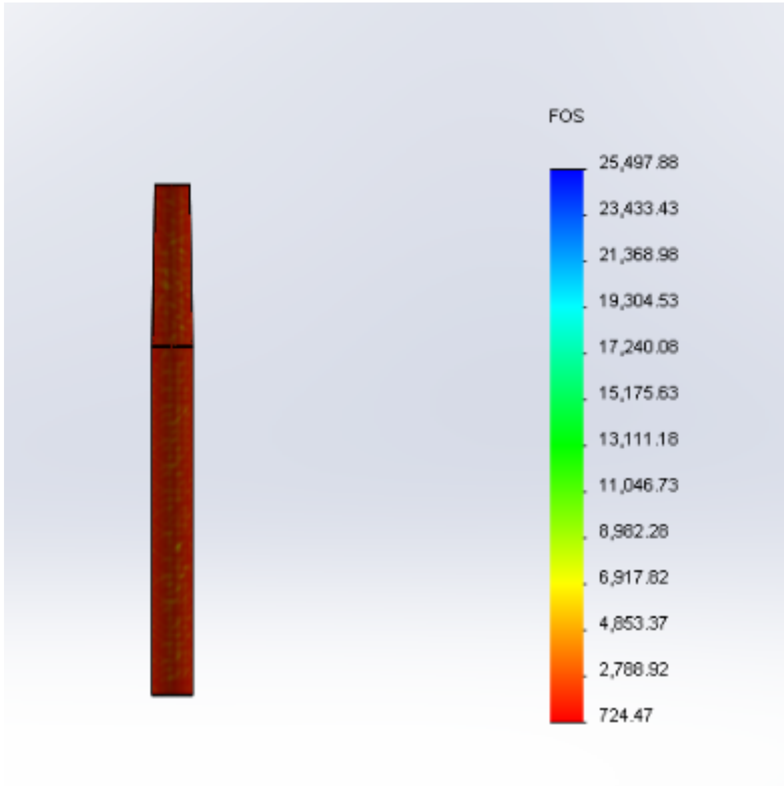


Figure 18: Finite Element Safety Analysis

These high numbers indicated a very remote chance of failure due to stress. As is typical of shafts in torsional load, the majority of the load was being carried by the outside layer of the spindle. Deformation Analysis was also conducted to provide insight into the allowable tolerances for the design. The results of Deformation Analysis (see **Figure 18**) showed that deformation varied between $1.782 * 10^{-4}$mm and $2.623 * 10^{-2}$mm.

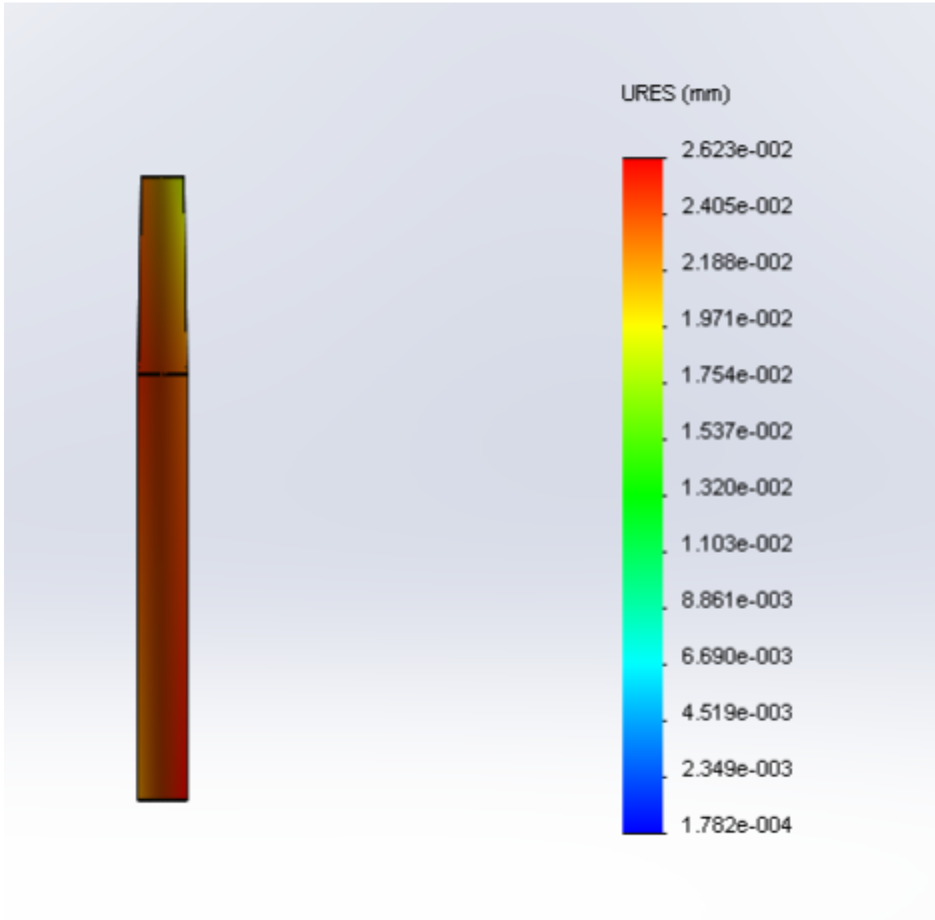


Figure 19: Finite Element Deflection Analysis

The areas of greatest deformation were on the outer layer of the lower part of the spindle. It was notable that the spindle's taper experienced less deformation than the rest of the spindle. Thus, in summary, the results of the Finite Element Analysis appear to indicate that the design for the spindle is adequate, if not overdesigned. Stresses fall well within allowable factors of safety and deformation is small compared to part dimensions. Independently, hand calculations for the shear stress were conducted and indicated that there was a factor of safety of 1505.5 (see **Appendix C3.5**). This only differs from the simulation by 5%, indicating that the simulation was fairly accurate.

3.2.3 Rotor

The rotor is the component that carries the sample holders while attached to the spindle (see **Figure 19**). Selecting the correct rotor was vital in meeting the specifications of the project. As mentioned in Section 2.4.1.2, deciding between a fixed angle rotor and a swinging bucket rotor had significant influence on the overall design of the centrifuge. Additionally, a larger rotor can carry more samples, but will generally require more power to spin and cost more. Conversely, a smaller rotor will carry a more limited number of samples, but require less power to spin and cost less.

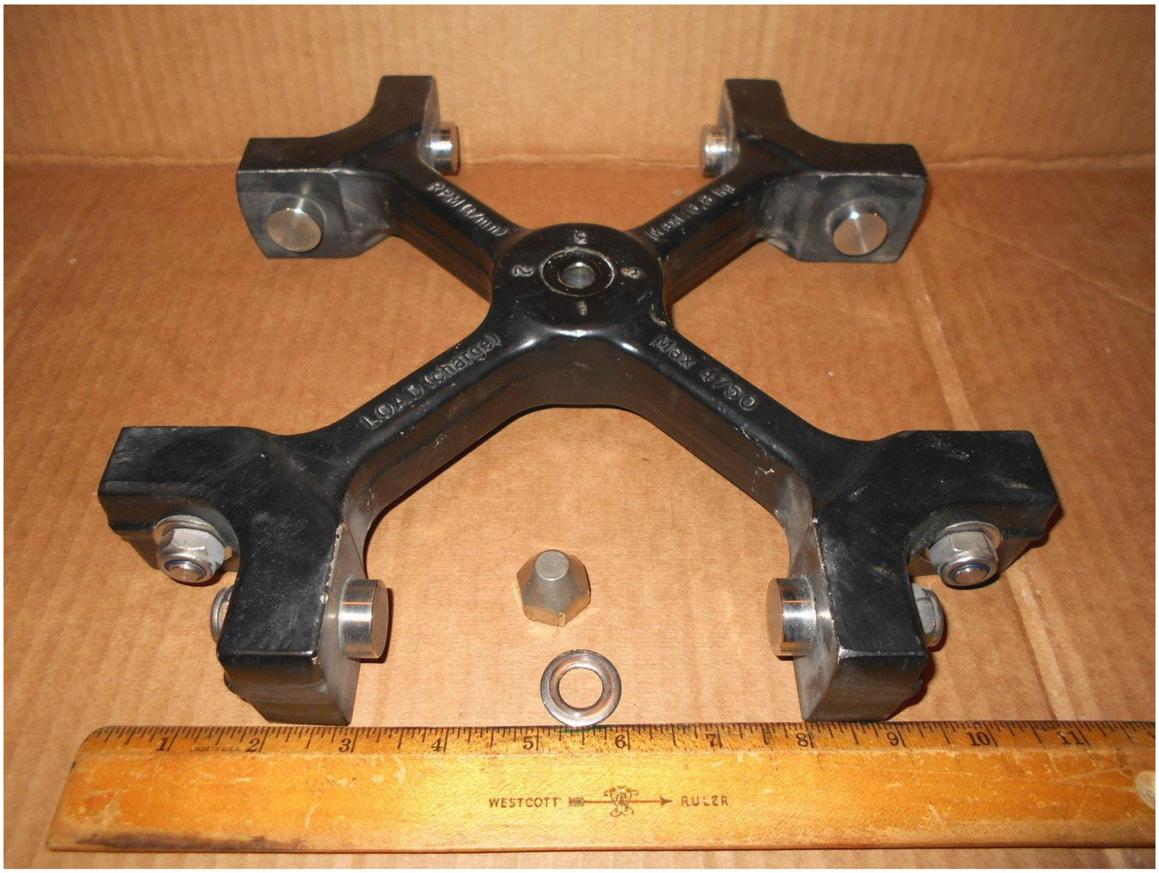


Figure 20: Jouan C4 Swinging Arm Rotor

The selected rotor, a Jouan C4 series, is rated to spin at up to $4750\ RPM$ and weighs 7.3 kg. The spindle connected through the center hole of the rotor, will transfer the rotational movement of the rotor.

Figure 21: Castle Nut and Cotter Pin

The spindle will then be locked in place by a castle nut and cotter pin (see **Figure 21**) to promote safety while the device is spinning. Buckets carrying samples will be placed on the four sides of the rotor to ensure that the specimens are rotated at the same speed as the rotor.

3.2.4 Sample Holders

The placement of samples is crucial in delivering accurate results in experiments. We had to make sure that the specimens experienced the same speed that the rotor was rotating in. The problem was solved by attaching sample buckets on the sides of the rotor. Two sizes of test tubes could be inserted into these bucket inserts. White adapters are able to host up to 9 test tubes of diameter $19.05\ mm$, while red adapters can hold up to 19 test tubes of diameter $15.875\ mm$. Additional adapters could be substituted to accommodate other sized test tubes. These adapters perfectly hold the test tubes in place even if the samples are rotating at extreme speeds of $4000\ RPM$.

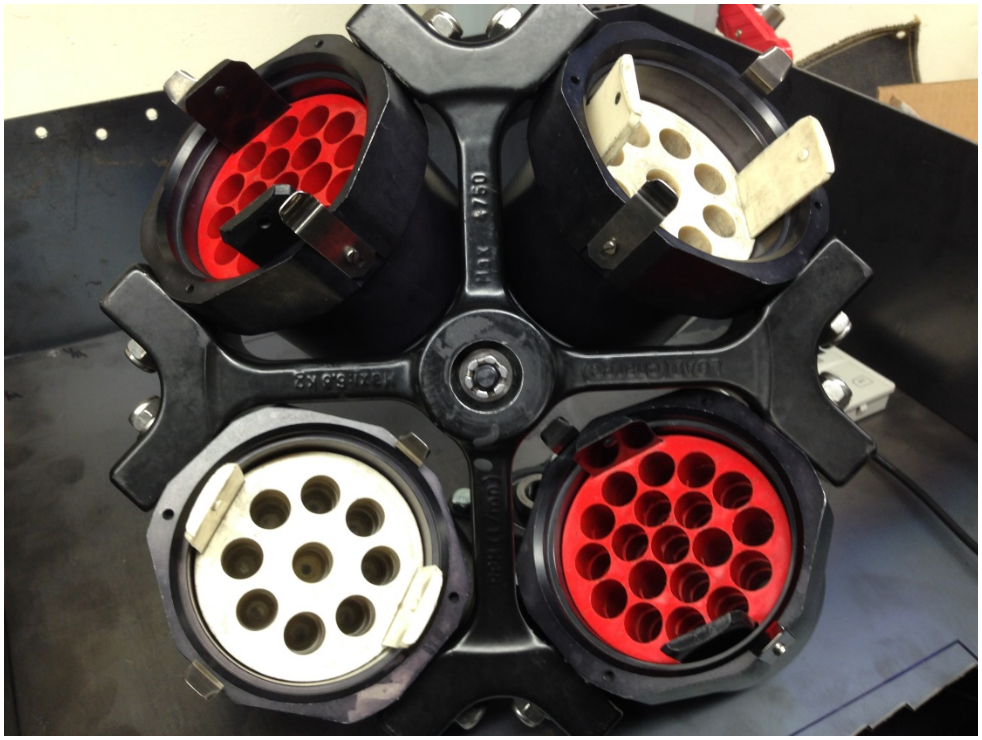


Figure 22: Sample Holders

3.3 Control System

The centrifuge's control system has three main areas of focus: the User Interface, the Speed Controller, and the Safety Features. A general overview of the control system is shown in **Figure 23**.

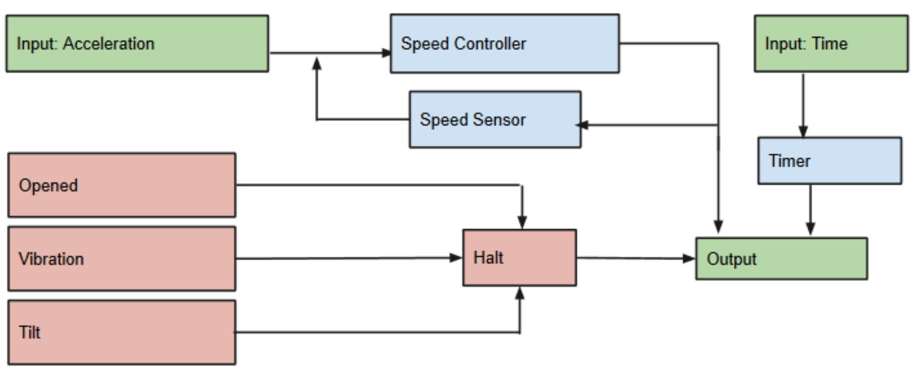


Figure 23: Control System Diagram

Each area of focus for the control system is color coded. User interface functions are colored green, speed controller functions are colored blue, and safety features are colored red.

3.3.1 User Interface

The User Interface is responsible for the way that the centrifuge receives input from the user and provides feedback. This ranges from the user inputting specifications about the speed and time that a particular sample should be spun to providing helpful error messages to help the user troubleshoot why the centrifuge is not working.

Figure 24: Control Module

In terms of input, this project intends to allow for both RPM and RCF to be accepted forms of speed input. Further, while there will be a time associated with all runs, there will also be an option to end a run early at any time (this is also one of the safety features).

Error messages are important for providing the user feedback about what is happening with the centrifuge. This will allow the user to correct problems that require the centrifuge to stop. This project intends to provide error messaging for at least the following situations: the rotor hatch is opened during a run, the centrifuge detects an abnormal amount of vibration, the centrifuge detects a tilt, and the user has manually terminated a run. Additional error messages may be implemented as they are called for.

3.3.2 Speed Controller

After receiving input from the user, the speed controller will achieve and maintain the specified speed for the specified duration. Feedback sensing would be handled by the sensors in the motor and driver. Although it is not implemented at this time, this project had planned to employ PID control for this goal. While it is not vitally important that the time constant of the system be minimized, it will be advantageous to have a lower one.

3.3.3 Safety Features

Safety is a primary concern of this project. As such, a number of features are devoted to avoiding dangerous situations and mitigating the effects of those that do arise. As described in Section 3.3.1, various error messages will be displayed to the user in the case that the centrifuge detects that it is being operated in an unsafe manner. In addition to that, the centrifuge's control system is designed to be able to stop at any point during a run. Emergency stops will be given the highest override privileges within the system.

Chapter 4 – Verification and System Integration

In order to ensure that the centrifuge functions properly, tests were conceived and conducted on each of the centrifuge's subsystems. These tests were conducted to verify that each component functioned as designed, as well as identify feasible areas for improvement.

4.1 Frame Verification

Since the frame of the centrifuge contains the rotor and solutions, it is important that it will be structurally sound even when the centrifuge is spinning at high speeds. Thus extensive analysis and testing was conducted to ensure the integrity of the frame. Detailed structural analysis and vibrational analysis were performed in order to determine the requirements of the frame. This included dynamics on the acceleration of the centrifuge as well as identifying the natural frequency of the centrifuge. We wanted this natural frequency to be dissimilar to any common frequencies that could be used when operating the centrifuge in order to avoid resonance. A more in depth description of these analysis can be found in the frame subsystem section 3.1. In addition to this analysis, test runs will be conducted on our centrifuge before it is released to the public. In these test runs, we will operate the centrifuge at slow speeds initially, in order to determine the integrity of the frame and to see if it remains stable.

Currently the frame is fully constructed and is very stable. The leveling feet helped to ensure that the frame is level and balanced, thus minimizing tilts and vibrations. Additionally, the analysis on the frame concluded that the frame can be relied upon to protect the user as the calculations proved that the frame could withstand the worst case scenario of impact.

4.2 Rotor Verification

Since the rotor could not be tested independently from the other parts, the rotor testing primarily consisted of assembling the subsystem with the frame and checking to see if everything functioned properly. The shaft was installed by attaching it to the motor and through the frame's bearing, and then the rotor was connected to the shaft. The rotor was then visually tested to determine if the parts had the correct tolerances. In this visual test, the main concern is checking to see if all of the parts fit snugly, as any loose fitting could cause unwanted vibrations. After installing the rotor subsystem and visually checking the parts, we found that the shaft did not fit into the motor as tight as we had wanted. We have since ordered a new custom shaft that fits the motor better. Additionally, the rotor was found to fit very well to the shaft as the taper was machined to specifically fit the rotor.

4.3 Control System Verification

The testing of the control system of the centrifuge will involve test runs of different components of the control system. The first test run will be to determine if the control system responds to the input. This will be done by having the user input a command into the control panel and then checking to see if the centrifuge responds to this command as desired. Another test run will be conducted in order to determine if the sensors work to sense emergency. This will be done by running the centrifuge at extremely low speeds with the swinging buckets intentionally loaded unbalanced. This will test whether the sensors operate correctly and determine that the centrifuge will not run in the event of imbalance. Similar testing will be conducted in order to evaluate the emergency halt system. In the event of imbalance or vibration that exceed the set allowable threshold, the emergency system should go into effect in order to halt the motion of the rotor. Additionally, a test will be run to verify that the centrifuge is spinning at the intended speed by entering a speed for it to spin at and then measuring it with a strobe tachometer. Lastly, a simple test run will be conducted to determine if the control system provides the user with feedback.

4.4 System Integration

Once the design of the three subsystems was completed, it was then necessary to integrate these subsystems together to form the completed unit. As the frame served as the foundation of the unit, it was assembled first, and the motor, spindle, rotor, and control system were then added. The steel plates of the frame were fastened using nuts, bolts, split washers, washers, and corner and side brackets. In order to fasten the motor to the frame, a mounting plate was designed and machined out of aluminum. The plate was milled to precisely fit the shape of the motor, and holes were drilled in order for the mount and motor to be fastened to the frame with bolts. The spindle was then integrated by fitting it into the motor and locked into place with the keyway. The control system was then installed with wires running through the hole in the back of the frame, and by connecting the control module to the motor. The steel plate and bearing were then installed with corner brackets on the inside of the frame. The rotor was added onto the top of the spindle and secured with a castle nut and cotter pin. This then allowed the lid to be attached to the back face of the frame using two hinges. Additionally, a latch could then be attached to the lid and front face of the frame.

With a fully assembled centrifuge, the user will be able to input the desired run parameters *via* the control system. The control system will then determine the output for the rotor. The rotor actuates the instructions of the control system and will spin the samples at the desired speed. During this process, the frame will be providing support to the system to help minimize any tilts and vibrations. The frame will also protect the operator during a run. Additionally, during a run, the control system will be sensing for tilts and vibrations and if any abnormalities are detected, it will signal for the centrifuge to stop.

Chapter 5 - Ethical Standards and Realistic Constraints

As engineers, we are bound to a particular set of standards, and as such, these standards hold a strong influence in the design process. In addition to these standards, our design is also largely influenced by limitations or constraints that are put upon us. The standards and constraints that most significantly impacted our design decisions include: ethics, safety concerns, manufacturability, economic concerns, and sustainability.

5.1 Ethics and Safety Concerns

As ethical designers, we are obligated to maintain a standard of safety for the use of our designs. Since we are designing a product for public use, it is absolutely essential that we ensure the product operates in a safe manner and functions as intended. If we are not able to ensure safe operation of our device and a properly working emergency system we are ethically bound to not release our product to the public. The reason for this “walk away” is that we have an ethical duty to the users of our product. An unsafe product could cause electrical shocks, burns, fire, or violently strike the operator, and if this were to happen, we would be held responsible for unsound and unethical design. However, if users of our centrifuge alter it in ways that we did not design, we are not responsible for any possible failures of the system. But as designers we should attempt to make alterations to the original design difficult in order to keep the centrifuge functioning as originally designed.

Our highest priority is to ensure the safety of the centrifuge’s operator and other people near the centrifuge when it is use. The Benchtop Centrifuge for Materials Science will accelerate solutions to speeds of up to 4000 RPM, which represents a significant risk of severe injury for any person who comes in contact with any of the fast moving parts. In order to prevent this from happening, a locking mechanism is designed in order to cover the moving parts and lock the cover in place. The lock will ensure that the cover will protect the operator even when the device is moving at high speeds.

Another serious safety concern is that at high speeds, the centrifuge could become unbalanced or something could get stuck in the rotor. This would cause the accelerating parts to move in a manner that the centrifuge is not designed to operate at and cause it to react violently, potentially seriously harming the operator or people nearby. In order to prevent this safety hazard, we designed an emergency system. During use, this system will be constantly determining if the centrifuge is rotating properly and if it is balanced. If at any point in time these conditions are not met, the emergency system will override current controls, shut the unit down, and stop the rotation of the centrifuge's rotor as quickly as possible.

However, since safety can often conflict with performance, we have conducted dynamics and vibration analysis to determine the maximum speeds the centrifuge can safely operate at. By taking these maximum speed values into account, we are enabled to design the system in such a way as to prevent the user from operating the centrifuge in unsafe conditions and design fail-safe mechanisms in the case of other failures.

Finally, extensive testing was conducted on our product before it is released for public use. Once we have a functional device, we will scrutinize it and note any imperfections and safety concerns that we did not anticipate. These problems will be addressed so that we can ensure the finished product will keep the operator safe.

5.2 Social and Manufacturability Concerns

The Benchtop Centrifuge for Materials Science will improve the availability of affordable centrifuge products, but also comes with the task of ensuring the safety of the user(s) and the proper function of the product itself. In creating an affordable centrifuge for materials science research, we also have a duty to ensure that the device that we design has a positive impact on society. Defects or oversights in the design of the centrifuge leading to unsafe conditions or improper processing of materials in a laboratory would be a violation of this standard and require a recall of the products. Because recalling products can be timely and expensive, these social considerations must be taken into account before the product is released to the market.

Foremost among the social considerations for this centrifuge is the misuse of the centrifuge. As mentioned in Section 5.1, the moving parts within the centrifuge represent a significant danger to any person(s) that may come into contact with them. While proper use and procedure for the centrifuge should protect the user from these dangers, improper or uninformed use of the centrifuge may instead increase in these dangers. Furthermore, increases in availability will affect both law-abiding institutions and illegal endeavors alike. A centrifuge in particular may be used for the creation of illegal substances. While the risk of these misuses does have negative social impact, the potential positive social impact outweighs them.

Other negative social impacts may also come from product malfunction. Careless design, undetected material defect, and fabrication error are all examples of vectors for product malfunction that may cause the centrifuge to fail to perform to specification. These malfunctions may threaten the safety of the user or the integrity of the product being separated.

We also made considerations of manufacturability in the design of the centrifuge. Having ease of fabrication has three main benefits. It reduces chance of fabrication error, it reduces cost of fabrication labor, and it reduces skill required for fabrication.

It is important to design a robust product that can function with wide tolerances because error in fabrication is a reality. By picking fabrication processes and specifications that reduce the chance or allow greater error, the product may continue functioning outside the ideal specification.

Fabrication labor costs money, and reducing the complexity of fabrication is one way that this team approached keeping the cost of the product down. By reducing the number of operations and complexity of the operations, the overall fabrication difficulty was reduced. This is especially important when attempting to scale the production of the product as any savings would then be multiplied throughout the fabrication process.

Because we would be personally fabricating the centrifuge prototype, our own skill in fabrication limited the types and complexity of modifications we were able to make. One example of this is the decision not to include thick metal plates in the design due to the fact that they would not be able to be processed using the equipment available to us in the fabrication lab.

5.3 Economic Concerns

As with any new product, the development of the Benchtop Centrifuge for Materials Science will have effects and be affected by the existing market. Both of these are areas that should be considered during the design of the product.

The effects of the existing market on this design are direct. Price will be a major factor in the quality of parts available for the design. For example, if the team is able to spend less money on one particular component, there will be more money in the budget for higher quality options for other components. However, if cost limitations require that a part or parts be fabricated personally, design complexity and accuracy will be constrained by team member time contribution and fabrication skills. As such, the prioritization of subsystem and component level budgeting is highly important to the success of this project.

While the scope of this project will not allow this centrifuge to be best in class of anything (professional design companies typically spend many more man-hours on such a project than 3 undergraduate students are capable of), there will still be some economic effects of this project. As such the team has prepared a business plan for the sale and distribution of the Benchtop Centrifuge for Materials Science in the case that sales becomes a possibility (see **Appendix D**).

Additionally, the successful completion of this project will provide Santa Clara University with a functioning centrifuge that it will not have to purchase. This will also enhance the materials science research capabilities of the School of Engineering. This will have effects on the nature of purchases the School of Engineering makes. For example, if a new lab exercise is designed to use the centrifuge, it may become necessary to purchase reagents for those exercises. Further, the purchase of less commonly produced materials may be reduced if use of the centrifuge enables the production of those materials from other reagents. Finally, enabling materials science research would potentially lead to the discovery of new information about materials, the use of which may change the demand for such materials. As such, the effects of this project are primarily economically positive.

5.4 Sustainability

One factor that we considered during our design process was sustainability. While not a primary factor in our design, we felt morally obligated to design our product to be as sustainable as possible while still meeting our primary design requirements and budget. We maximized the sustainability of our centrifuge by designing it to have a relatively long lifetime. Due to the quality materials and parts that we have chosen, we have ensured that the centrifuge will last for years. By maximizing the lifetime of our product, we are helping the environment as the long lifetime helps the user to avoid having to purchase a whole new unit after a short period of time. If our centrifuge did not have a long lifetime, the user would need to replace the device after a short period, meaning that the environment would be negatively affected since more waste would be produced. In addition to the long lifetime, the Benchtop Centrifuge for Materials Science will also incorporate a modular design. This means that the individual parts work separately so that in the case of a part failure or a desire to upgrade, the user can replace a single part rather than the entire product. Additionally, this provided options for reducing cost by purchasing individual parts from the least expensive distributor.

Chapter 6 – Conclusion

As we conclude our work on the centrifuge, we have considered the successes and failures that we have experienced with this project. We have evaluated areas that could be addressed in the future, and have also assessed what we have accomplished throughout our work.

6.1 Future Work

In order to continue improving the design of the Benchtop Centrifuge for Materials Science, we have identified these areas of improvement to be addressed in a future iteration.

With the frame, we found some difficulties with machinability and fabrication. In particular, we found that our simple frame design limited the strength that we were able to harness within the frame, which caused the centrifuge to be heavier and bulkier than necessary for the amount of protection it was providing.

After installing the shaft of our centrifuge into our motor, we found that the fit was looser than we had wanted. Thus, we had to order a new custom shaft that would fit the motor more snugly. Unfortunately due to the late arrival of the part, we only had time to machine the taper of the shaft, but were not able to fully install it.

The control system is also a potential area for improvement. Because none of our team members had expertise in electrical engineering, we had to use a particularly inelegant solution for the wiring in order to get power to each component. With better electrical design, those needs could be met more efficiently. Additionally, we experienced complications involving the transformer for our control system which caused it to be unsafe to operate. With further time, we would have purchased a different transformer that would allow us to safely operate our device.

Due to problems involving the rotor and control system, we decided to not waste our budget on purchasing a lid for the frame until these issues were resolved. However, a lid could easily be installed using the hinges and lock that we have purchased.

We have also prepared advice on some of the challenges and specific areas of study relevant to this particular project for future teams in **Appendix E**.

6.2 Summary

The Benchtop Centrifuge for Materials Science was designed to be a versatile, cost-effective, user-friendly and safe centrifuge for the university setting. It aimed to improve availability of laboratory equipment by providing adequate performance for a reduced cost. Work on the centrifuge lead to various forms of analysis including Natural Frequency Analysis and Finite Element Analysis and the majority of the frame was complete and ready for integration with the other subsystems, but poor planning and delays in assembly prevented a prototype from being completed. In the future, continuers of this project may wish to take the opportunity to improve the designs and complete the project.

References

1. Ed. K. Lee Lerner and Brenda Wilmoth Lerner,"Centrifuges," in *The Gale Encyclopedia of Science* Vol. 1. 4th ed. Detroit: Gale, 2008. p857-858.

2. S. Rangarajan, "Centrifuge Technology," in *Special Focus on Centrifuges*, 2010.

3. John Shelton, John Rogers Smith, Anuj Gupta, "Experimental Evaluation of Separation Methods for a Riser Dilution," in *Approach to Dual Density Drilling,* Journal of Energy Resources Technology, 2011.

4. Current Opinion in Neurobiology, 1997, Vol.7(5), pp. iii-iii) Peer-Reviewed Journal.

5. Cheol Hoon Park, Soohyun Kim, and Kyung-Soo Ki, "Review of Scientific Instruments 84, 095106," AIP Publishing, 2013.

6. http://www.flottweg.de/global/product-line/decanter/industrial-centrifuges.html

7. http://www.mohawkmedicalmall.com

8. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

9. http://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/torsion.pdf

10. http://web.aeromech.usyd.edu.au/AMME2301/Documents/mos/Chapter04.pdf

Appendix A - Design Specifications

A1. Benchmarking Comparison

Benchmark System 1: QBC® Horizon 755VES Centrifuge

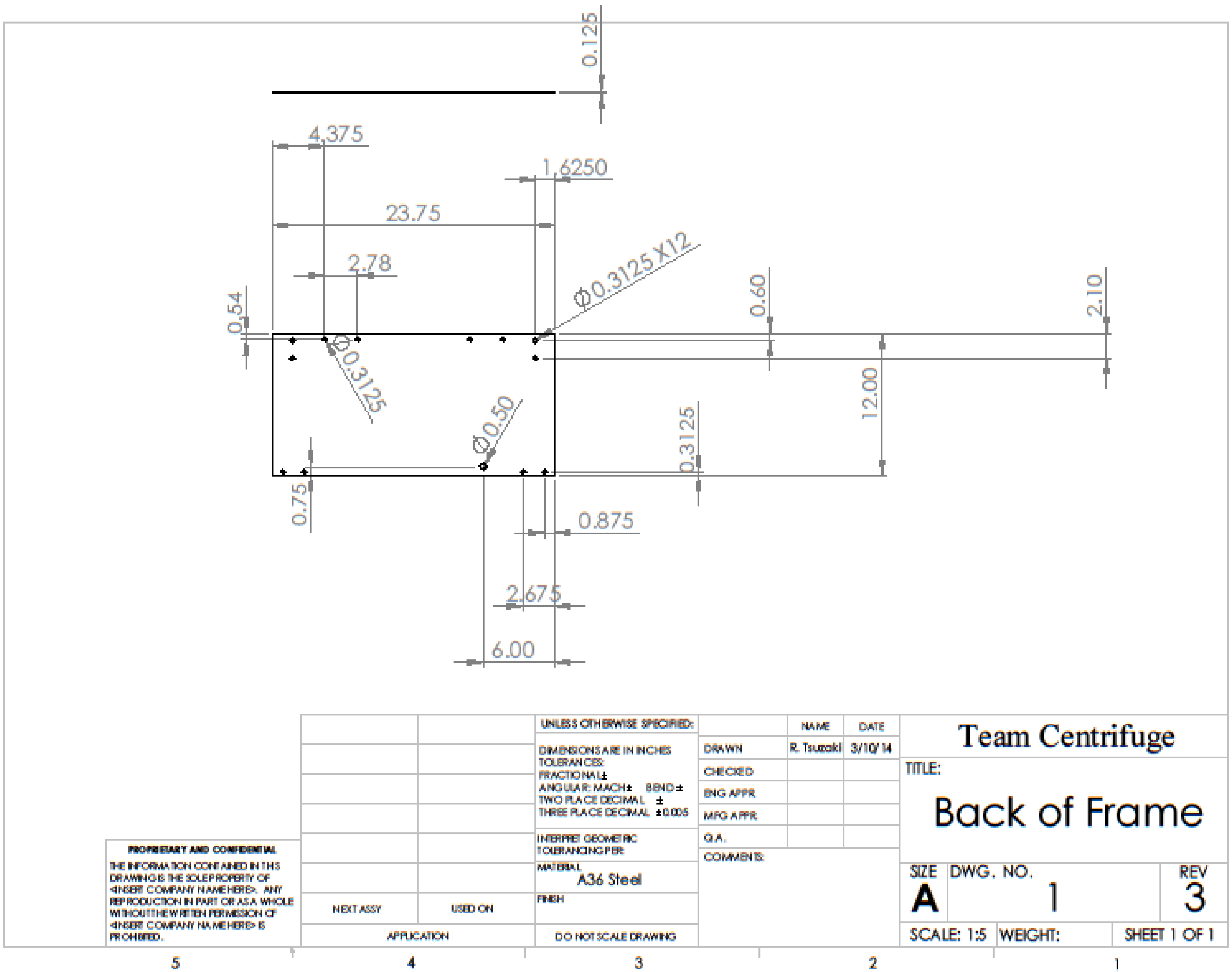
Benchmark System 2: Heraeus™ Labofuge™ 400 Centrifuges

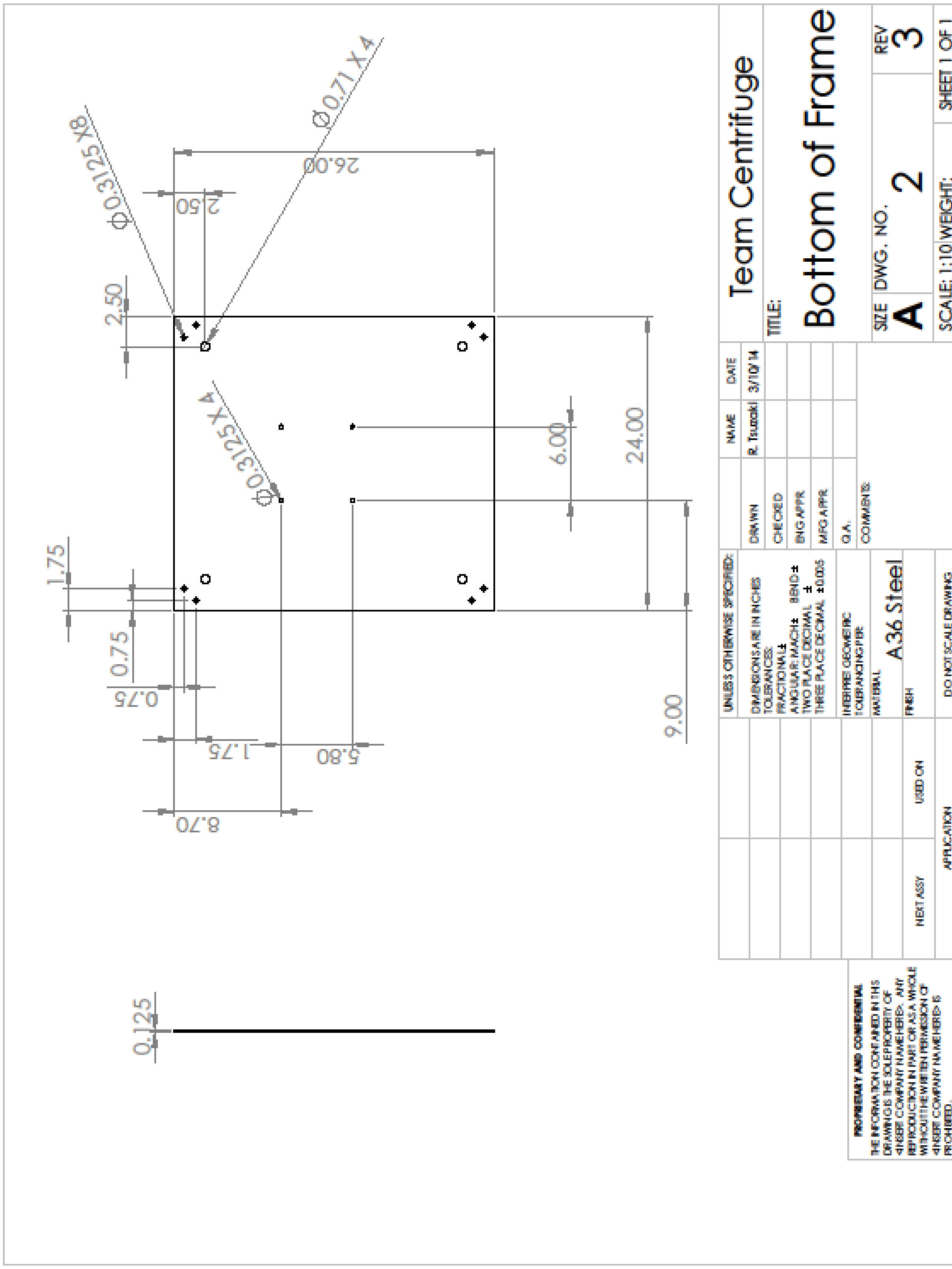
Benchmark System 3: Horizon Centrifuge Model 853VES

*Design criticality is rated on a scale from 1 (most critical) to 5 (least critical)

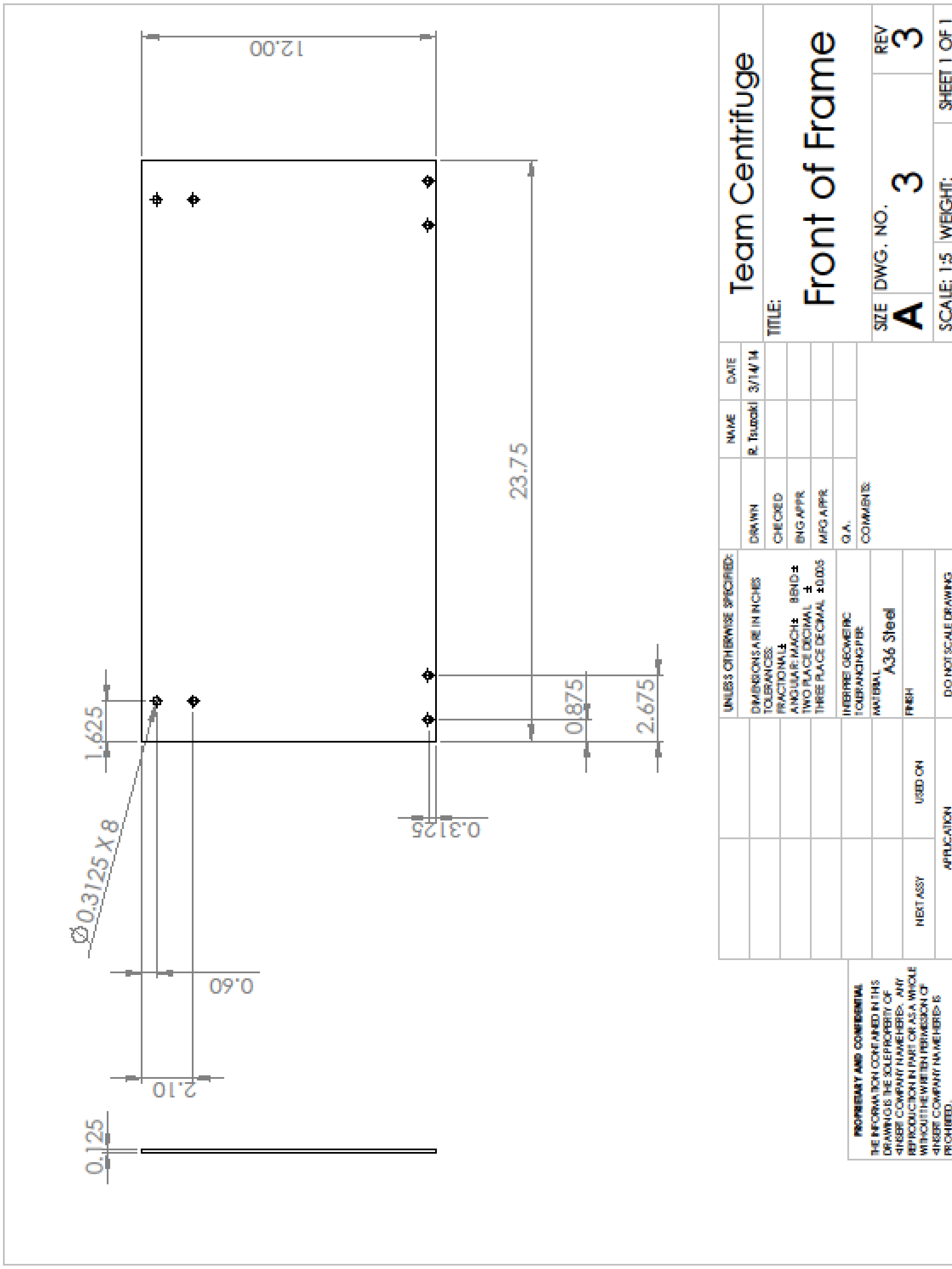
Parameter [Units]	Benchmark #1	Benchmark #2	Benchmark #3	Design Target	Design Criticality
Capacity [mL]	-	720	300	400	3
Min Speed [RPM]	500	300	500	500	4
Max Speed [RPM]	4300	11,500	4,000	3,500	2
Max RCF [g]	3,200	12,000	2,000	5,000	1
Weight [lbs]	39	88	30	75	4
Dimensions [in]	14.5*17*9	22.4*17.2*12.2	8.5*12.5*15.5	27*24*12	2
Cost [$]	$3000	-	$3300	$1800	1
Emergency Response [sec]	-	-	-	10	1
Power [W]	200	-	200	200	4

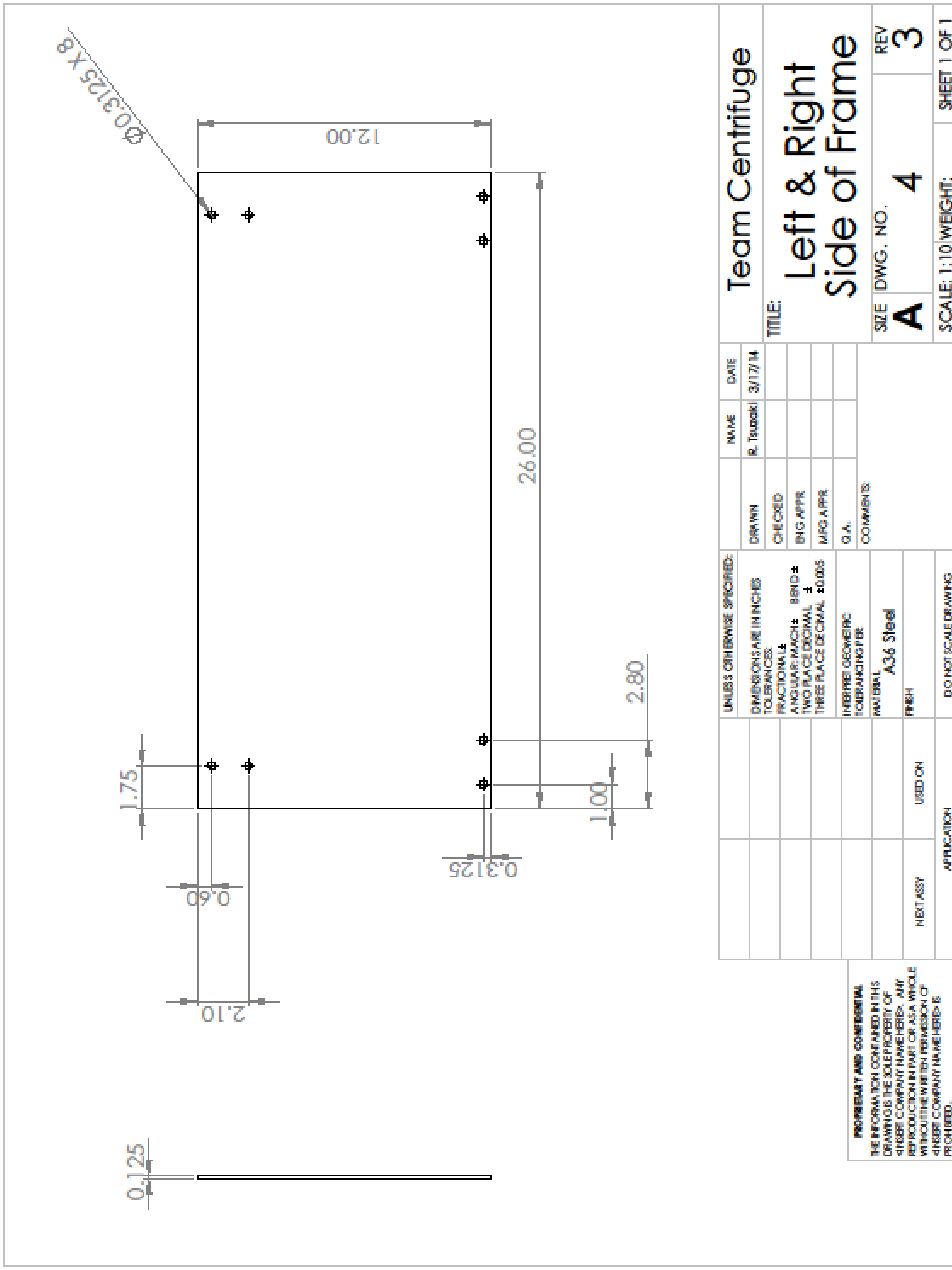
Lifetime [yrs]	-	-	2	4	3
Min Acceleration Time [sec]	15	-	15	60	4
Min Deceleration Time [sec]	15	-	22	60	4
Operating Temperature [°C]	2 to 35	-10 to 40	-	0 to 40	4
Timer Capabilities [min]	0:99	1:99	0:99	0:99	3
End-of-Run Chime [y/n]	-	-	yes	yes	3
Timer Precision [%]	±1	-	-	±1	4

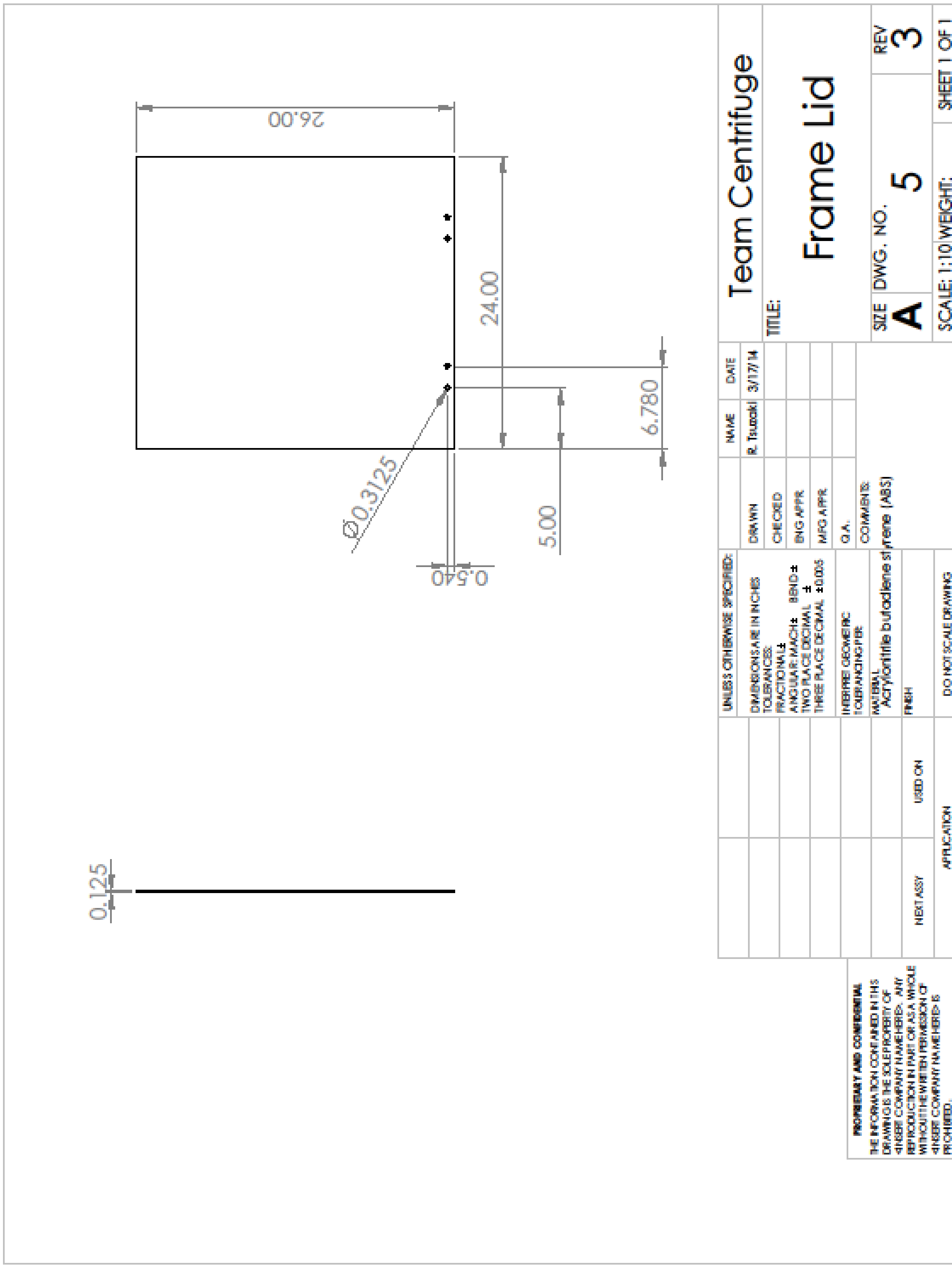

0.125
4.375
1.6250
23.75
2.78
Ø0.3125 X12
0.60
2.10
0.54
Ø0.3125
Ø0.50
12.00
0.3125
0.75
0.875
2.675
6.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
A36 Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
R. Tsuzaki
3/10/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Team Centrifuge
TITLE:
Back of Frame
SIZE
A
DWG. NO.
1
REV
3
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
5
4
3
2
1



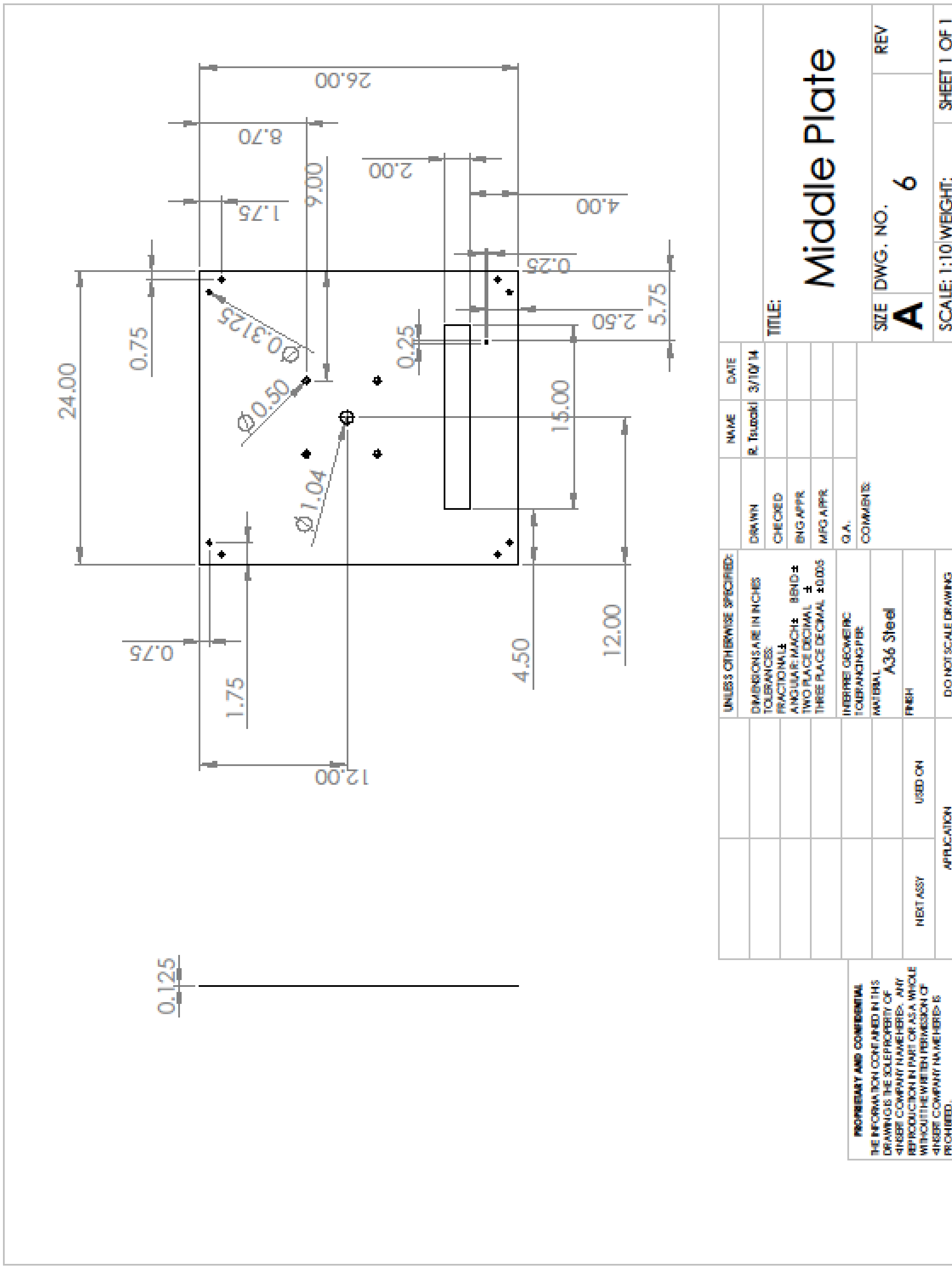
Team Centrifuge
TITLE:
Bottom of Frame
SIZE A
DWG. NO. 2
REV 3
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
A36 Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
R. Tsuzaki
3/10/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
Ø0.3125 X8
Ø0.71 X4
Ø0.3125 X4
26.00
24.00
2.50
2.50
6.00
9.00
1.75
0.75
0.75
1.75
5.80
8.70
0.125
1
2
3
4
5

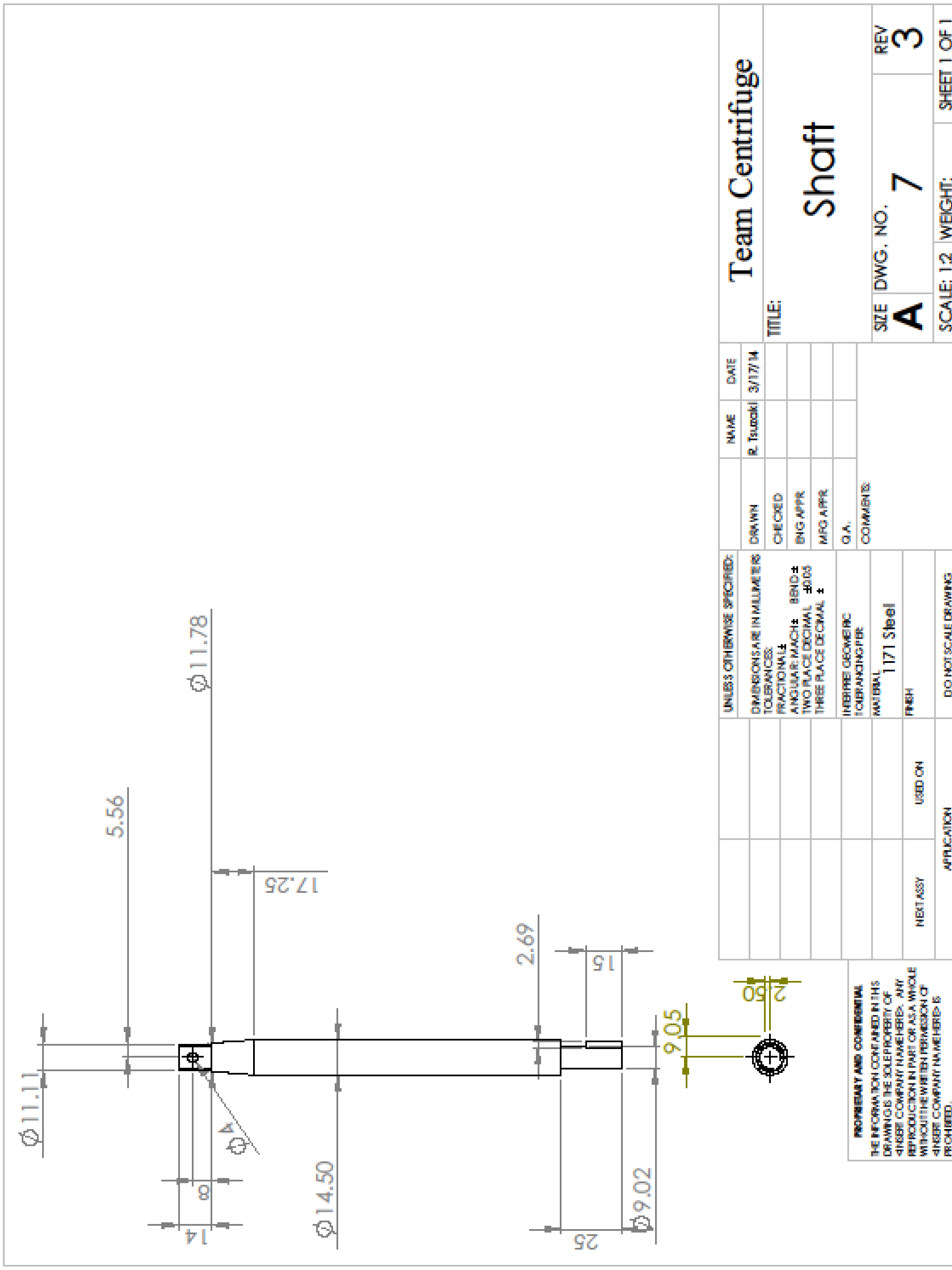

12.00
23.75
1.625
0.875
2.675
0.3125
Ø0.3125 X 8
0.60
2.10
0.125
Team Centrifuge
TITLE:
Front of Frame
SIZE A
DWG. NO. 3
REV 3
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
DRAWN R. Tsuzaki 3/14/14
NAME
DATE
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
A36 Steel
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

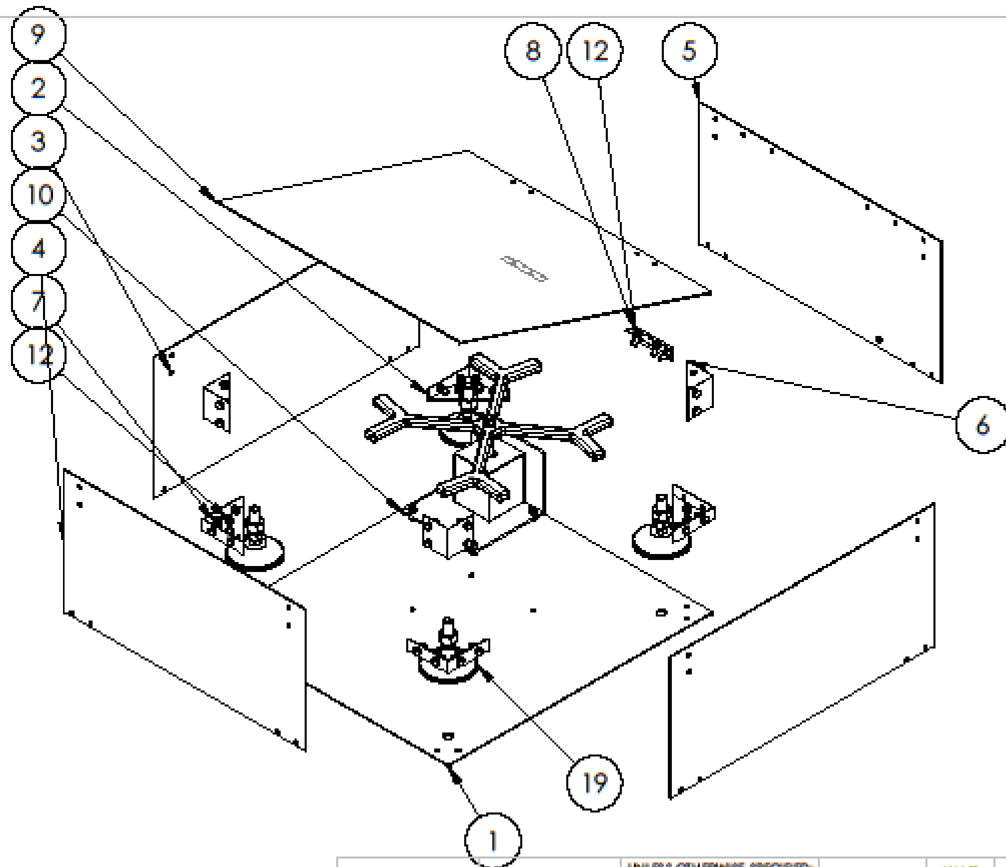

Ø0.3125 X 8
12.00
26.00
2.80
1.75
1.00
0.3125
0.60
2.10
0.125
Team Centrifuge
TITLE:
Left & Right
Side of Frame
SIZE A
DWG. NO. 4
REV 3
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
A36 Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
R. Tsuzaki
3/17/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.



26.00
24.00
6.780
5.00
Ø0.3125
0.540
0.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylonitrile butadiene styrene (ABS)
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
R. Tsuzaki
3/17/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Team Centrifuge
TITLE:
Frame Lid
SIZE
A
DWG. NO.
5
REV
3
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
1
2
3
4
5


26.00
8.70
9.00
2.00
1.75
4.00
0.25
24.00
0.75
Ø0.3125
Ø0.50
0.25
2.50
5.75
15.00
Ø1.04
0.75
1.75
4.50
12.00
12.00
0.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
A36 Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
R. Tsuzaki
3/10/14
TITLE:
Middle Plate
SIZE
A
DWG. NO.
6
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
1
2
3
4
5


Team Centrifuge
TITLE:
Shaft
SIZE
A
DWG. NO.
7
REV
3
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1171 Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
R. Tsuzaki
3/17/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
Ø11.11
5.56
Ø11.78
17.25
2.69
15
2.50
9.05
14
8
Ø4
Ø14.50
25
Ø9.02
1
2
3
4
5



ITEM NO.	PART NUMBER	QTY.
1	Bottom of Frame	1
2	Corner Bracket	4
3	Left Side of Frame	2
4	Front of Frame	1
5	Back of frame	1
6	Edge Connector	4
7	HNUT 0.3125-18-D-C	41
8	Hinge Assembly	2
9	Lid	1
10	Mount	1
11	Tapered assembly	1
12	HBOLT 0.3125-18x0.75x0.75-C	50
13	Simplified motor	1
14	Preferred Narrow FW 0.4375	1
15	Inner Part of Motor (keyway)	1
16	HSNUT 0.4375-14-D-S	1
17	Shaft	1
18	Rotor	1
19	Foot Leveler	4

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

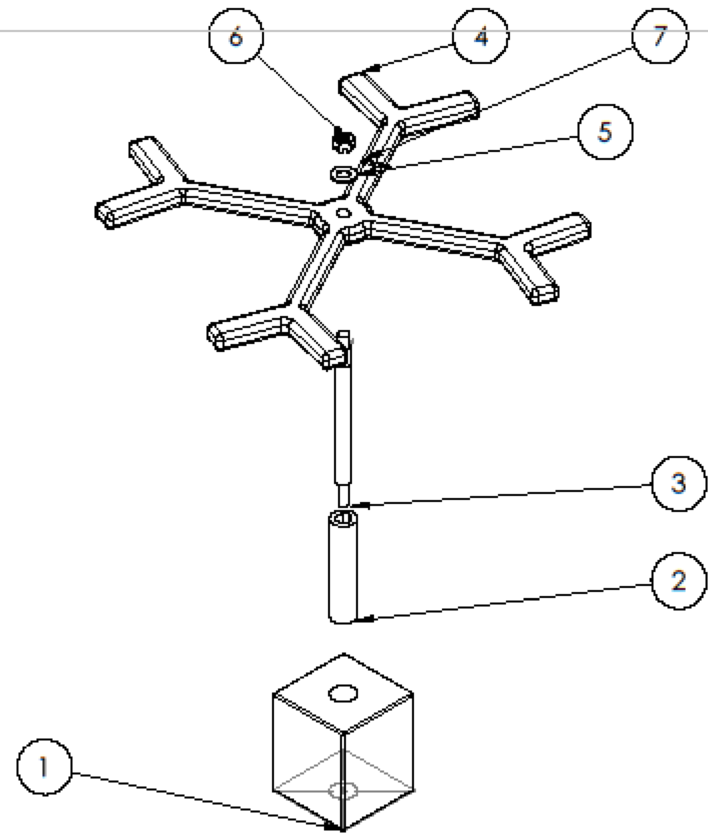
	NAME	DATE
DRAWN	R. Tsuzaki	3/19/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

Frame Assembly

SIZE A | DWG. NO. 8 | REV
SCALE: 1:20 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	QTY.
1	Simplified motor	1
2	Inner Part of Motor (keyway)	1
3	Shaft	1
4	Rotor	1
5	Preferred Narrow FW 0.4375	1
6	HSNUT 0.4375-14-D-S	1
7	Castle Nut Cotter Pin	1

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

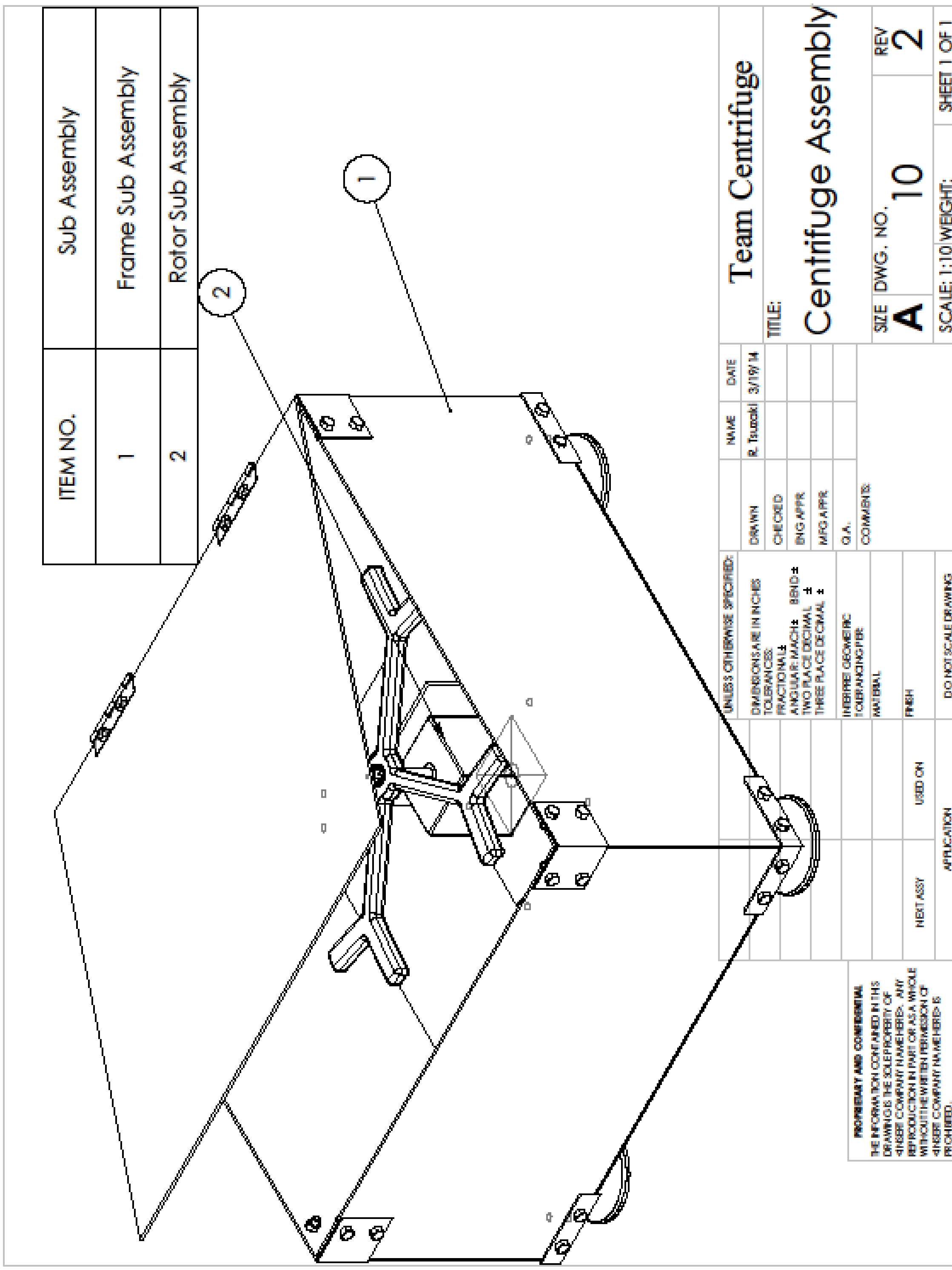
NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	R. Tsuzaki	3/17/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

Team Centrifuge
TITLE:
Rotor Assembly
SIZE A | DWG. NO. 9 | REV 3
SCALE: 1:20 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



ITEM NO.
Sub Assembly
1
Frame Sub Assembly
2
Rotor Sub Assembly
1
2
Team Centrifuge
TITLE:
Centrifuge Assembly
DRAWN
R. Tsuzaki
3/19/14
SIZE
A
DWG. NO.
10
REV
2
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
DO NOT SCALE DRAWING

Appendix B: Project Management Data

B1. Project Budget

Income:

Department of Mechanical Engineering	$1800

Costs:

Rotor	$280
Motor	$900
Raw materials (Frame & Motor Mount)	$250
Rotor Spindle	$80
Fasteners	$75
Labor Costs	$200
Total:	$1785

B2. Project Timeline

Fall Quarter:

Week 5	• Team Dynamics Reflective Report • Research
Week 6	• Conduct surveys on customer needs • Research
Week 7	• Customer Needs Report. • Research
Week 8	• CDR draft
Week 9	• Initial dynamics analysis
Week 10	• CDR Final

Winter Quarter:

Week 1	• Finalize dynamics analysis • Begin control system design

	• Design prototype • Shop for supplies
Week 2	• Finish shopping for supplies • Design prototype
Week 3	• Work on prototype
Week 4	• Work on prototype
Week 5	• Finish Prototype
Week 6	• Finish control system
Week 7	• Testing of prototype
Week 8	• Testing of prototype
Week 9	• Assembly Drawings & Initial Hardware Due
Week 10	• Assembly Drawings & Initial Hardware Due

Spring Quarter

Week 1	• Work on final product
Week 2	• Work on final product
Week 3	• Finish final product
Week 4	• Testing • Work on presentation
Week 5	• Final adjustments • Work on presentation
Week 6	• Present

Week 7	• Work on thesis
Week 8	• Work on thesis
Week 9	• Work on thesis
Week 10	• Finish thesis

Appendix C - Design Analysis Results

C1. Maximum Allowable Design Load for Joint in Shear

$\tau_{yp} = 57{,}000$ psi

A= Cross sectional area of bolt= 0.049 in

F_s= Factor of safety=2

P= Maximum allowable load

Since there are 12 bolts per face the following should hold true:

$$\frac{P}{12 \times A} \leq \frac{\tau_{yp}}{F_s}$$

$P \leq 11172$ lb

C2. Impact Force of Bucket When Centrifuge is Spinning 4000 RPM

v= linear velocity
d= rotor diameter= 0.3905 m
RPM= 4000

$$v = \frac{\pi * d * RPM}{60}$$

= 81.786 m/s

F= Impact force

m= Mass of bucket= 0.5 kg

s= Distance for bucket to slow down= 0.5 in= 0.0127 m

$$F = \frac{m * v^2}{s}$$

= 29601.1 lb

Since there are 12 bolts per face the following should hold true:

UTS= Ultimate tensile strength of bolt= 120,000 psi

A= Cross sectional area of bolt= 0.049 in

F_s= Factor of safety=2

$$\frac{F}{/12} \leq \frac{UTS}{xA/Fs}$$

$$2466 \quad \text{lb} \leq 2940 \text{ lb}$$

C3. Shaft Torsion

Rotor's Moment of Inertia = 0.046112 kg m-^{2}

Max speed = 4000 RPM= 419 rad/s

Shaft Diameter = 14 mm

1045 Cold Rolled Steel Shear Strength = 450 MPa

C3.1. Angular Acceleration Required to Reach Max Speed

$\alpha = (\omega - \omega_o)/ t$

Assuming max speed is reached in 2 minutes (120 seconds)

$\alpha = (419 - 0) / 120$

$\alpha = 3.492$ rad/s^2

C3.2. Torque Required to Reach Max Speed in 2 Minutes

T = I * α

T = 0.046112 * 3.492

T = 0.161023 Nm

C3.3. Moment of Inertia of Circular Shaft

$J = \Pi*(D_{shaft})^4 / 32$

$J = \Pi*(0.014)^4/ 32$

$J = 3.771 * 10^{-9}\ m^4$

C3.4. Torsional Stress in Circular Shaft

$\tau_{max} =$ T * R-$_{outer}$ / J

$\tau_{max} =$ 0.161023 * (0.014/2) / 3.771 * 10^{-9}

$\tau_{max} =$ 298903 Pa

C3.5. Factor of Safety of Shaft

FOS = Yield Strength / Max Stress

FOS = 450 * 10^{6} / 298903

FOS = 1505.5

Appendix D: Business Plan

The Benchtop Centrifuge for Materials Science is intended to be a low price product specifically for the university research market. The draw of the product is its low price point of $2,000 while still meeting the requirements of laboratory needs. This low price point was achieved by specifically tailoring the product for the University market, and through bulk order discounts on supplies. Using the business plan outlined below, the team believes it could achieve a project value of $268,727.62, while returning the initial investment in the first six months.

D1. Introduction/Background

Research and verification of material properties is vital in any design of a physical product. In order to fabricate the material intended for research, isolating reagents by compound and mass are often required. This isolation of reagents can be accomplished for solutions by sedimentation, or the settling of particles suspended in a solution. While gravity produces the effects of sedimentation naturally, this can be expedited by applying additional acceleration to the particles. This is commonly done in centrifuges, which apply these addition accelerations by spinning their samples.

D2. Goals and Objectives

The Benchtop Centrifuge for Material Science is intended to be a low price product specifically for the university research market. The team hopes to achieve a return on investment within 6 months.

D3. Description of Product

The Benchtop Centrifuge for Material Science offers cost-effective materials refining capabilities. By spinning its samples at high speeds, it can expedite the settling of different parts of the sample based upon their density. This can be used to purify specific reagents or filter for the mass of particles, both of which are necessary steps in many material fabrication processes.

D4. Potential Markets

The Benchtop Centrifuge for Materials Science is designed for the small laboratory setting. It's easy set-up, simple run procedure, and low price make it ideal for frugal or new laboratories. Initial markets will focus on the University Research setting, specifically Santa Clara University, expanding as manufacturing plans and demand for the product improve.

D5. Competition

The primary competition for the Benchtop Centrifuge for Materials Science are other centrifuges in the industry. Our competition will primarily be fairly small centrifuge units that would commonly be seen in labs, similar to the centrifuges that we researched in our benchmarking. These centrifuges that are currently on the market were found to cost around $3000-$5000. By carefully selecting necessary features to implement, the design of the Benchtop Centrifuge for Materials Science has managed to be produced at a much lower price, at times as much as half or one third the price of its competition.

D6. Sales/Marketing Strategies

Many competing centrifuges have rotational speeds into the tens of thousands of revolutions per minute. While having this upper bound is impressive, within the purview of typical material refinement and fabrication, it is often unnecessary. Instead, by focusing on offering good cost-effectiveness, the Benchtop Centrifuge for Material Science will serve the laboratories that are looking for a lower price with adequate performance for most tasks. The team plans to market our product by contacting and meeting with Universities. We will focus on emphasizing the cost-effectiveness of our product compared to the other options of centrifuges currently on the market.

D7. Manufacturing Plans

Benchtop Centrifuge for Material Science would have parts ordered separately before assembled, modified, and tested in a private and enclosed setting such as a garage. A minimum of 30 days is required to ensure the product is ready to hit the market. This duration includes shipment of different parts, modifications, and testing. The frame materials would be ordered and machined by MaxxMetals, which would take about two weeks to finish. OrientalMotors would also take two weeks to ship the motor together with its driver and control module. The centrifuge rotor could be shipped in a week. MisumiUSA would also need two weeks to ship the connecting shaft. Parts modifications and assembly would take about a week after the parts have arrived, and finally another week for product verifications through testing.

D8. Product Costs

Based off of our research on suppliers, we found that we would be able to receive discounted pricing by ordering in bulk. However, since we do not have the funds to order everything at once in a single order, our suppliers were able to provide quotes on prices based off of a discount given for ordering a large amount annually, rather than for a single order. The table below represents pricing for the various parts required to build 5 centrifuge units. Note that these prices are considerably lower than what we paid for our first model due to the bulk pricing.

Steel Plates	$220.00
Motors	$3,000.00
Shafts	$100.00
Fasteners	$80.00
Bearings	$80.00
Total Cost	$3,480.00

D9. Services or Warranties

The team strongly believes that the device will function optimally in the first two years of operation. Therefore a two year warranty would be provided at the time of the purchase of Benchtop Centrifuge for Material Science. Warranty will protect our customers' purchase by replacing faulty parts that were received immediately after shipment. If the malfunctioning parts were found to be reparable, the team would offer a charged service for repairs.

D10. Financial Plan

Our financial plan was largely influenced by our available budget that can be put into the initial investment, as well as the costs for the materials for our centrifuges. While we may have been able to get cheaper prices on materials by ordering in larger quantities, it was determined that we would only have an available budget for an initial investment of 5 centrifuge units. Luckily it was determined that suppliers would provide discount prices based on the amount of units we purchase annually, rather than units that we purchase with each order. Based on prices given by suppliers, we concluded the price per 5 centrifuges would be $3,480.00. Since we will be recent graduates, we will not have much to invest initially. We decided we would initially invest in 5 units and would spend 3 months getting everything prepared. After this period, we assumed we would sell one unit during our first month of sales and that we would sell each centrifuge for $2000 as this would provide a significant profit while still providing a cheaper price than the rest of the market. We believe that our monthly sales will increase by 1 unit each month and that we would spend $100 monthly to meet with and negotiate with customers. Since we were able to acquire a deal with our material suppliers for prices based on our annual order, we decided it would not be necessary to order too much volume at a time. By ordering a smaller amount at a time, we could help to reduce any risks of investing too much at once. Therefore, we plan to invest in the 5 units in the initial month, then increase the number of units we order each month. Based on this plan we determined that we would have a return of investment within 6 months. And if we continue this business for two years, we would have a project value of $268,727.62, taking a 3% inflation rate into account. After these two years, we assume that we would stop production as we would most likely have sold to all the colleges in the area by this time. Also note that a return in investment would be achieved in the sixth month. Further detail of the business plan can be seen in **Appendix D11**.

D11. Business Plan Spreadsheet

TEAM CENTRIFUGE	
Initial Costs (For 5 Units)	
Steel Plates	$220.00
Motors	$3,000.00
Shafts	$100.00
Fasteners	$80.00

Bearings	$80.00
Total Initial Investment	$3,480.00

Month	1	2	3	4	5	6	7
Monthly Costs							
Marketing	$0.00	$0.00	$100.00	$100.00	$100.00	$100.00	$100.00
Production Cost Per 5 Units	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00
Production Volume	5	0	0	0	0	5	5
Total Cost	$3,480.00	$0.00	$100.00	$100.00	$100.00	$3,580.00	$3,580.00
Unit Sales							
Sales Price	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00
Sales Volume	0	0	0	1	2	3	4
Sales Income	$0.00	$0.00	$0.00	$2,000.00	$4,000.00	$6,000.00	$8,000.00
DB Period Cash Flow	-$6,960.00	$0.00	-$100.00	$1,900.00	$3,900.00	$2,420.00	$4,420.00
Db Cumulative Cash Flow	-$6,960.00	-$6,960.00	-$7,060.00	-$5,160.00	-$1,260.00	$1,160.00	$5,580.00
PV, month	-$6,960.00	$0.00	-$99.50	$1,885.82	$3,861.24	$2,389.98	$4,354.28

Month	8	9	10	11	12	13	14
Monthly Costs							

Marketing	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Production Cost Per 5 Units	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00
Production Volume	6	7	8	9	10	11	12
Total Cost	$4,276.00	$4,972.00	$5,668.00	$6,364.00	$7,060.00	$7,756.00	$8,452.00
Unit Sales							
Sales Price	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00
Sales Volume	5	6	7	8	9	10	11
Sales Income	$10,000.00	$12,000.00	$14,000.00	$16,000.00	$18,000.00	$20,000.00	$22,000.00
DB Period Cash Flow	$5,724.00	$7,028.00	$8,332.00	$9,636.00	$10,940.00	$12,244.00	$13,548.00
Db Cumulative Cash Flow	$11,304.00	$18,332.00	$26,664.00	$36,300.00	$47,240.00	$59,484.00	$73,032.00
PV, month	$5,624.82	$6,889.01	$8,146.85	$9,398.38	$10,643.61	$11,882.58	$13,115.30

Month	15	16	17	18	19	20	21
Monthly Costs							
Marketing	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Production Cost Per 5 Units	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00	$3,480.00
Production Volume	13	14	15	16	17	18	19
Total Cost	$9,148.00	$9,844.00	$10,540.00	$11,236.00	$11,932.00	$12,628.00	$13,324.00
Unit Sales							
Sales Price	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00
Sales Volume	12	13	14	15	16	17	18
Sales Income	$24,000.00	$26,000.00	$28,000.00	$30,000.00	$32,000.00	$34,000.00	$36,000.00
DB Period Cash Flow	$14,852.00	$16,156.00	$17,460.00	$18,764.00	$20,068.00	$21,372.00	$22,676.00
Db Cumulative Cash Flow	$87,884.00	$104,040.00	$121,500.00	$140,264.00	$160,332.00	$181,704.00	$204,380.00
PV, month	$14,341.80	$15,562.10	$16,776.22	$17,984.19	$19,186.03	$20,381.77	$21,571.42

Month	22	23	24
Monthly Costs			
Marketing	$100.00	$100.00	$100.00
Production Cost Per 5 Units	$3,480.00	$3,480.00	$3,480.00
Production Volume	20	21	22
Total Cost	$14,020.00	$14,716.00	$15,412.00
Unit Sales			
Sales Price	$2,000.00	$2,000.00	$2,000.00
Sales Volume	19	20	21
Sales Income	$38,000.00	$40,000.00	$42,000.00
DB Period Cash Flow	$23,980.00	$25,284.00	$26,588.00
Db Cumulative Cash Flow	$228,360.00	$253,644.00	$280,232.00
PV, month	$22,755.02	$23,932.57	$25,104.11

Total Spent	$178,288.00
Project PV	$268,727.62
Inflation Rate	
3.00%	

Appendix E: Posterity Documentation

Building a centrifuge can be deceptively complicated. Our team has listed some lessons we've learned for posterity.

Analysis Topics

These are topics of study that were useful to understand in the design of the centrifuge. Full understanding is not required, but you will probably encounter most of these topics:

Dynamics - Vibrations and Natural Frequency

Dynamics - Eccentric Rotation (Tilt Thresholds)

Drive Mechanisms - Transferring Torque, Fasteners and Fail Safes

Fracture Analysis - Wall Thickness and Form

Shear Analysis - Rotor Shaft Diameter (FEA)

Electronics - Wiring and Electrical Power

Controls - User Interface Design

Machine Design - Frame Design and Fabrication

General Tips

These are miscellaneous tips that could prove to be very useful:

Get parts early, make sure to factor in shipping time (aim to have parts arrive mid Winter Quarter)

Get new parts, or make sure there is a lot of documentation, making measurements of your used parts is not ideal (and impossible in fatigue analysis)

Know all the parameters you need before purchasing a part, but don't let that stall progress

Funding is important: centrifuges are usually around the price range of $5000

Best of luck!

-2014 Centrifuge Team

Appendix F: Senior Design Conference Slides

SANTA CLARA UNIVERSITY

BENCHTOP CENTRIFUGE FOR MATERIALS SCIENCE

Jose Lizheno · Nathaniel Tseng · Ryan Tsuzaki
Under Advising of: Dr. Robert Marks

SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

PART 1: WHAT IS A CENTRIFUGE?

Introduction

Customer Needs

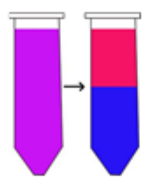
Problem Statement

SANTA CLARA UNIVERSITY

Introduction

Material Science and Mechanical Engineering

- Important to know material properties
- Isolate reagents to fabricate materials for research
- Use sedimentation to isolate



SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

Introduction (Cont.)

Why make a centrifuge?

- Centrifuges apply acceleration to expedite sedimentation
- SCU's Materials Lab lacks a centrifuge
  - Enable demonstration of industry procedure
  - Advance Materials Science Research at SCU

SANTA CLARA UNIVERSITY

Customer Needs

What kind of centrifuge is needed?

- Customer: SCU Materials Lab
  - Surveys, Interviews, Lit. Analysis
    - Versatile
    - Cost-Effective
    - User-Friendly
    - Safe

SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

Problem Statement

Breaking Down the Customer Needs

- Versatile
  - Fit on benchtop, not too heavy
  - Wide range of run speeds
- User-Friendly
  - Less complicated, save user's time
- Cost-Effective
  - Under $1,500
  - Long lifetime, low maintenance

SANTA CLARA UNIVERSITY

Safety Considerations

Ensuring User Safety

- Problems
  - High speed moving parts
  - Disturbances (vibrations/tilts) increase stresses
- Mitigations
  - Conducted failure analysis
  - Implemented emergency response features

SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

PART 2: THE SUB-SYSTEMS

Frame

Rotor

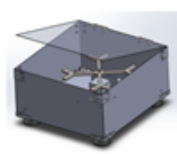
Control System

SANTA CLARA UNIVERSITY

Sub-System: Frame

Provides Support and Safety

- Provides Stability
  - Bearing supports rotor
- Protects user and centrifuge
  - Strain Energy Analysis
  - Emergency Brake



SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

Frame: Strain Energy

Preventing Wall Fracture

1. Calculate Kinetic Energy of Sample Holder
   - $m = 1\ kg,\ v = 7.3513\ m/s$ (180 RPM)
   - $KE = \frac{1}{2}mv^2 = 27.020\ J$
2. Calculate Collision Area
   - $C = 0.314\ m,\ t = 3.175 * 10^{-3} m$ (1/8 in)
   - $A = C * t = 9.880 * 10^{-4}\ m^2$
3. Calculate Applied Strain Energy
   - $G_{applied} = \frac{KE}{A} = 27{,}349.093\ Pa * m$

SANTA CLARA UNIVERSITY

Strain Energy (Cont.)

Preventing Wall Fracture

4. Calculate Allowable Strain Energy
   - $K_{Ic} = 119\ MPa * m^{1/2},\ E = 200{,}000\ MPa,\ v = 0.3$
   - $G_{crit} = \frac{K_{Ic}^2}{E/(1-v^2)} = 64{,}432.55\ Pa * m$
5. Compare Applied to Allowable
   - $N_{FoS} = 2,\ G_{applied} = 27{,}349.093$
   - $G_{crit}/N_{FoS} = 32{,}216.275\ Pa * m \geq G_{applied}$

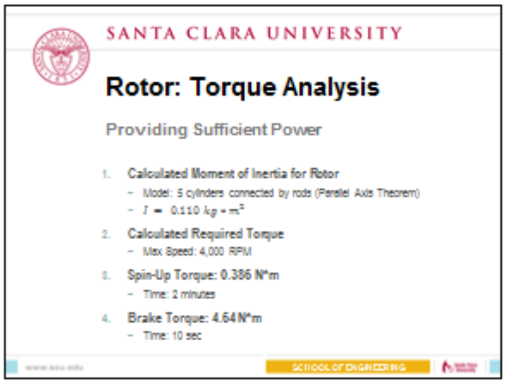
SCHOOL OF ENGINEERING

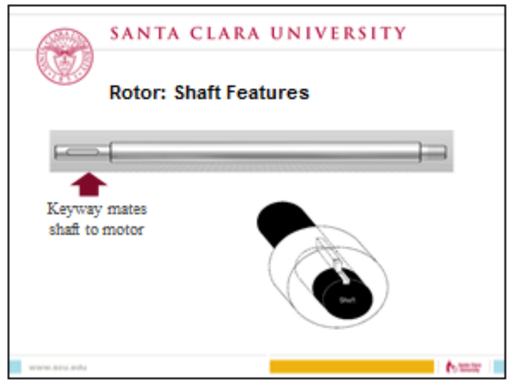
SANTA CLARA UNIVERSITY

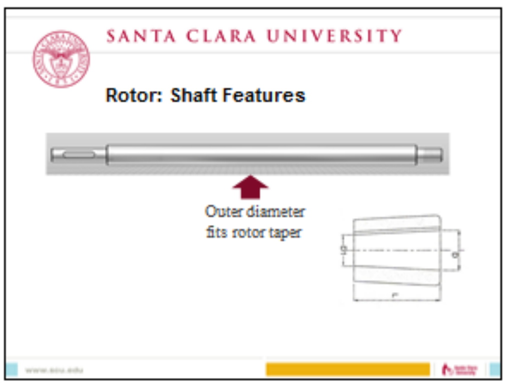
Sub-System: Rotor

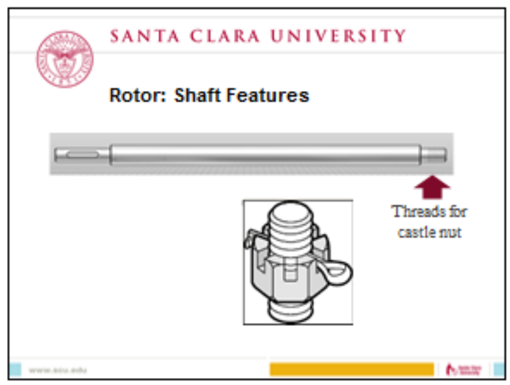
Efficiently Transferring Power

- Holds the Samples
  - Torque calculations using moment of inertia
  - Finite element analysis on shaft stresses
- Connects the Parts
  - Drive mechanisms transfer torque
  - Shaft is tapered to fit rotor

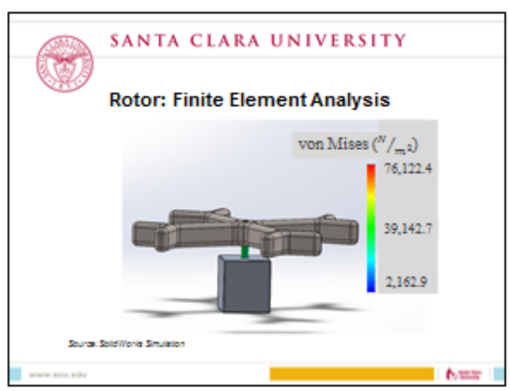

SANTA CLARA UNIVERSITY
Rotor: Torque Analysis
Providing Sufficient Power
1. Calculated Moment of Inertia for Rotor
– Model: 5 cylinders connected by rods (Parallel Axis Theorem)
– $I = 0.110\ kg * m^2$
2. Calculated Required Torque
– Max Speed: 4,000 RPM
3. Spin-Up Torque: 0.386 N*m
– Time: 2 minutes
4. Brake Torque: 4.64 N*m
– Time: 10 sec
SCHOOL OF ENGINEERING


SANTA CLARA UNIVERSITY
Rotor: Shaft Features
Keyway mates shaft to motor


SANTA CLARA UNIVERSITY
Rotor: Shaft Features
Outer diameter fits rotor taper


SANTA CLARA UNIVERSITY
Rotor: Shaft Features
Threads for castle nut


SANTA CLARA UNIVERSITY
Rotor: Shaft Taper
SCHOOL OF ENGINEERING


SANTA CLARA UNIVERSITY
Rotor: Finite Element Analysis
von Mises (N/m^2)
76,122.4
39,142.7
2,162.9
Source: SolidWorks Simulation

SANTA CLARA UNIVERSITY

Sub-System: Controls System

Interprets Input and Controls Output

- User Interface
  - Primary source of user input
  - Provides error messages to aid troubleshooting
- Determining Output
  - Input (RPM or g-force) to voltage
- Emergency Response
  - Mechanical analysis informs safety thresholds

SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

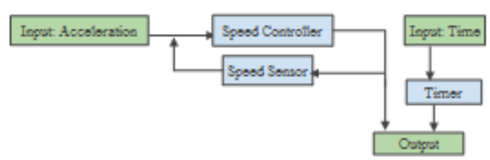
Controls: Overview

SANTA CLARA UNIVERSITY

Controls: Overview

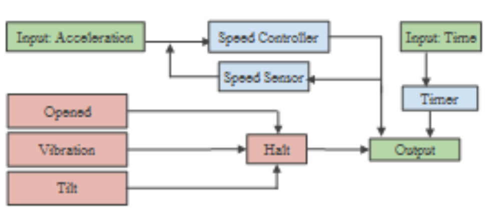
SANTA CLARA UNIVERSITY

Controls: Overview



SANTA CLARA UNIVERSITY

Controls: Overview



SANTA CLARA UNIVERSITY

PART 3: REALISTIC CONSTRAINTS

Future Work

Conclusion

SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

Future Work

Addressing Project Limitations

- Mechanical Design
  - Rotor Efficiency
  - Aesthetic
- Electrical Design
  - Wiring & electrical efficiency
  - User Interface

SANTA CLARA UNIVERSITY

Conclusion

- Centrifuge Design
  - Versatile
  - Cost-Effective
  - User-Friendly
  - Safe
- Sub-Systems
  - Frame
  - Rotor
  - Control System
- Construction
  - Analysis
  - Shaft Design
  - Frame Assembly
- Future Work
  - Mechanical design
  - Electrical design

SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY

Questions?